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Glacial stratigraphy of southeastern North Dakota

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GLACIAL STRATIGRAPHY OF SOUTHEASTERN NORTH DAKOTA

by

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This thesis submitted by Michael Camara in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota is hereby approved by the Faculty Advisory Committee under whom the work has been done.

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ABSTRACT

Seven lithostratigraphic units are recognized in the glacial sediment (till) of southeastern North Dakota. Five of these units are not formally named; eventually most of these units will be correlated with formations in surrounding regions. Two of these units, Gardar and Dahlen, are formations recognized in northeastern North Dakota (Hobbs, 1975). The seven lithostratigraphic units are differentiated and correlated using the percentage of the sand, silt, and clay fractions of the till and using the proportion of igneous and metamorphic rock fragments, limestone and dolomite fragments, and shale fragments in the very-coarse-sand fraction (1 to 2 mm) of the till. The proportions of sand and shale are the most important field criteria for identifying the units in this area and, along with stratigraphic position, are the primary criteria for distinguishing the units.

The lower three units, A, B, and C are recognized only in Ransom County, southern Barnes County, and in northern Sargent County. The Gardar Formation is recognized in LaMoure, Barnes, Ransom, and Sargent Counties and the Dahlen Formation and unit D are recognized throughout the study area with exception of Wells County. Unit E, the youngest lithostratigraphic unit in the area, is recognized only in Wells, Stutsman, and LaMoure Counties.

Where observed, the uppermost lithostratigraphic units cross three previously recognized end moraines in southeastern North Dakota:

the Grace City, the Oakes, and the Luverne End Moraines. On the basis of the lithostratigraphy of the glacial sediment of southeastern North Dakota, these arcuate ridges may be overriden older terminal moraines or they may not even be terminal moraines and new criteria must be used for recognizing terminal moraines in this area.

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The University of North Dakota, 1977

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INTRODUCTION

General

About two-thirds of North Dakota is covered by thick deposits of glacial sediment. My work with the glacial sediment of southeastern North Dakota has led to the recognition of at least seven lithostratigraphic units. The units are well exposed along the trenches of the James and Sheyenne Rivers and can also be recognized in the numerous testholes drilled by the North Dakota State Water Commission.

Area of Study

Most of my field work was done in the Sheyenne River trench in the western half of Ransom County and in the area of the James River trench from Carrington to Grand Rapids. The area of study is within the Drift Prairie of southeastern North Dakota (Figure 1).

Purpose

The purpose of this study was to interpret the Pleistocene history of southeastern North Dakota. The interpretation is based on a lithostratigraphic framework established by examining surface and subsurface samples of glacial sediment (till).

Methods

Purpose

The layers of drift of southeastern North Dakota have been differentiated from each other by analyzing the generally continuous layers

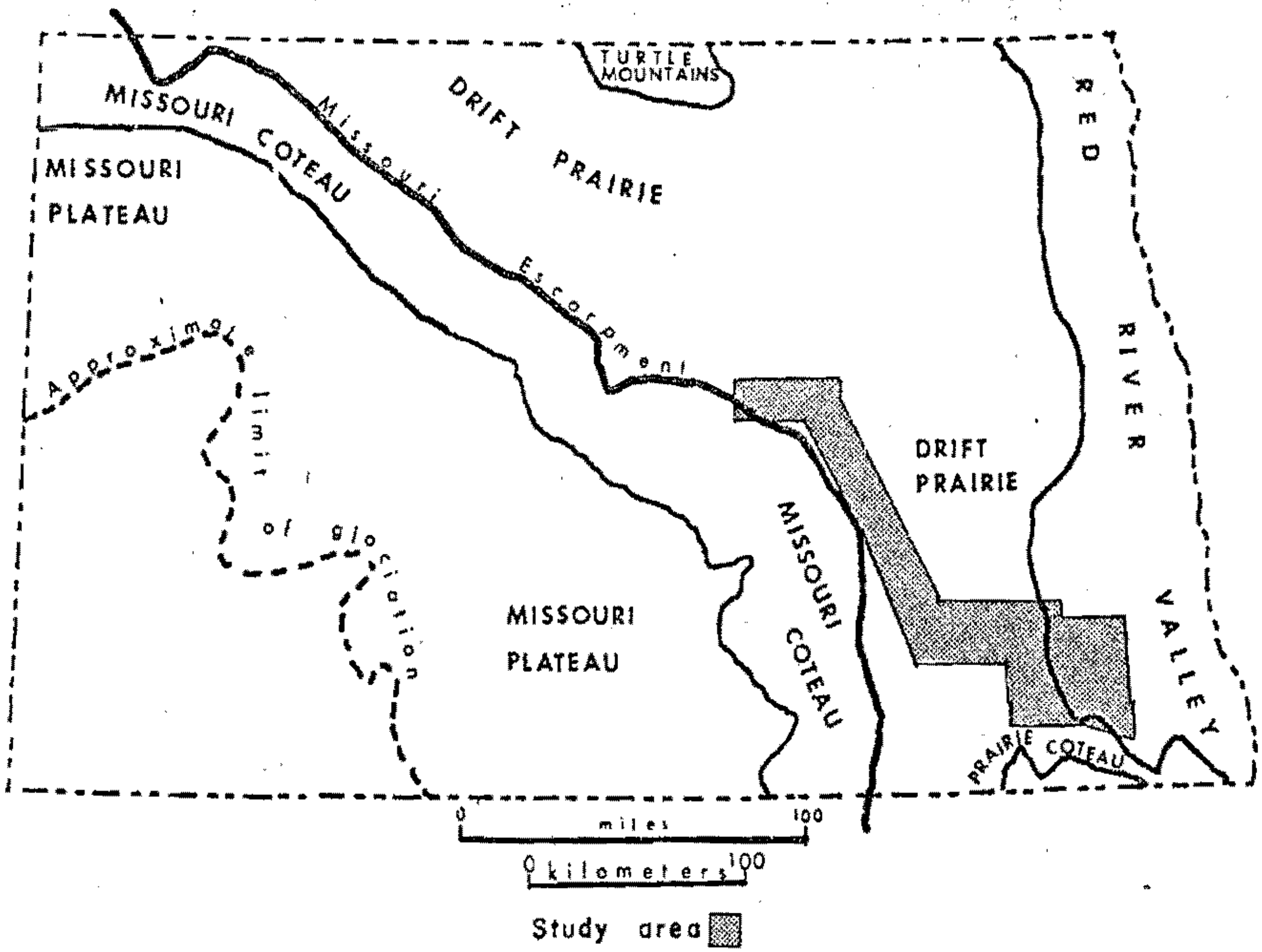

Fig. 1. Location of Study Area in North Dakota.

of till within the drift. This is possible because the physical and petrological characteristics of till are constant or vary in a predictable manner over a large area (Moran and others, 1975).

The petrological characteristics of till also may reveal the source area of the till because most till contains particles derived from bedrock that differs from the unit on which the till lies (Flint, 1971). A vertical change in the petrography of the rock particles within the till may demonstrate that the glacier flowed over terranes of differing petrography because the clasts in the till are derived from the substrate, at least in the case of continental ice sheets. If the mechanisms of glacial erosion remain unchanged throughout a glacial episode, a change in petrological composition of till may indicate a different source area for the till. But two or more tills having different petrographies do not necessarily demonstrate two or more separate glaciations because source areas of differing petrography may lie close to each other. For example, northeastern North Dakota serves as a source area for limestone and dolomite and shale because there are subcrops of Cretaceous shale and limestone and dolomite of the Ordovician System.

Multiple tills of differing petrography may, however, result from a changing direction of flow or from a change in the mechanisms of glacial erosion during a glacial episode. Thus, two or more lithostratigraphic units may form the sediment deposited as a result of a single glacial episode. For example, multiple till layers are recognized in the peripheral part of every large glaciated area (Goldthwait, 1971). Therefore, care must be taken in interpreting the significance of differing lithologies for till units.

Differentiation

The units of glacial sediment in southeastern North Dakota are differentiated from each other and correlated by determining the grain-size distribution (texture) and the lithologic composition of the very-coarse-sand fraction of the till.

A single grain size, the very-coarse-sand fraction (1 to 2 mm), was chosen for quantitative studies to determine any significant trends in till composition and provenance. This size range was chosen for the following reasons: the fragments of this size range are abundant in any sample of till weighing 41 grams, the lithologic composition of the sand of this size range is easily determined with a binocular microscope, previous work in northeastern North Dakota (Salomon, 1975 and Hobbs, 1975) used this same size, permitting regional correlations to be made, and the shale fragments of this size, particularly important in eastern North Dakota, are not susceptible to mechanical breakdown (Matsch, 1971). "Thus, a shale-fragment abundance close to that of the till at the time of deposition can be determined" (Matsch, 1971, p. 30).

The lithologic composition of the very-coarse-sand fraction is defined as the proportion of igneous and metamorphic rock fragments, limestone and dolomite fragments, and shale fragments in the very-coarse-sand fraction of the till.

The grain-size distribution (texture) is the proportion of sand, silt, and clay in the till matrix. The grain-size distribution of the till was analyzed so that additional data could be used for differentiating the units and because previous work in the state (Salomon, 1975 and Hobbs, 1975) has included this parameter in the lithostratigraphic frameworks developed.

The proportions of sand and shale were found to be the most important field criteria for differentiating till units in the study area and are the primary criteria for correlating the till units.

Lithostratigraphy

The American Commission on Stratigraphic Nonemclature (1970, p. 5) defines a lithostratigraphic unit as "a subdivision of the rocks in the earth's crust distinguished and delimited on the basis of lithologic characteristics as well as stratigraphic position."

Seven lithostratigraphic units are recognized in the glacial sediment of southeastern North Dakota. Five of these units are not formally named; two of the units, the Gardar and Dahlen Formations, have been previously recognized in northeastern North Dakota (Hobbs, 1975). Reference sections, descriptions, and differentiation criteria for each unit are presented in Appendix B.

PREVIOUS WORK IN SOUTHEASTERN NORTH DAKOTA

Lithostratigraphy

During the summer of 1973, David Huff (Geology Department, University of North Dakota) worked on the lithostratigraphy of the glacial sediment along the Sheyenne River trench in Griggs, Barnes, and Ransom Counties. He differentiated the various till units by analyzing the grain-size distribution (texture) and the lithologic composition of the very-coarse-sand fraction of the till. His work helped formulate a tentative lithostratigraphy.

Prior to Huff's work there was little work done on the lithostratigraphic framework of the glacial sediment of southeastern North Dakota. John Brophy (Geology Department, North Dakota State University, verbal communication, 1976) analyzed the glacial deposits of eastern Ransom County but no lithostratigraphic framework was developed. Block (1965) and Kelly and Block (1965) recognized a stratigraphic sequence of units of glacial sediment in Barnes County but neither one distinguished successive tills by lithology.

Previous reports (Todd, 1896; Hard, 1929; Kresl, 1956; Lemke and Colton, 1958; Colton, Lemke, and Lindvall, 1963; and Clayton, 1966) included surficial geologic mapping but provided no differentiation of the units of glacial sediment based on the petrological composition of the till.

Morphostratigraphy

Previous workers in North Dakota (Todd, 1896; Hard, 1929; Kresl, 1956; Lemke and Colton, 1958; Colton, Lemke, and Lindvall, 1963; Block, 1965; Clayton, 1966; and Kelly and Block, 1965) have mapped units which would be classified as a general type of morphostratigraphic units, event-stratigraphic units (also called ecostratigraphic units by Krumbein and Sloss, 1963).

Frye and Willman (1962, p. 112) defined a morphostratigraphic unit as "comprising a body of rock that is identified primarily from the surface form it displays; it may or may not be distinctive lithologically from contiguous units; it may or may not transgress time throughout its extent."

Ecostratigraphic units consist of the sediment deposited as the result of a distinct geologic event such as a glacial advance (Clayton, Geology Department, University of North Dakota, personal communication, 1976). The ecostratigraphic units of glacial sediment in North Dakota were differentiated from each other using any available criteria. For example, the presence of outwash gravel might have been used to indicate an ice margin. Clayton (1966, p. 12) recognized each ecostratigraphic unit of surface drift of southeastern North Dakota "by the presence of an end moraine behind which is nearly flat ground moraine." Therefore, there has been no intention by previous workers to map what would be called now morphostratigraphic units as defined by Frye and Willman (1962). However, in most places, surface morphology has been the primary criterion in recognizing an ecostratigraphic unit of glacial sediment. The definition of an ecostratigraphic unit aptly applies to the type of unit previously mapped in North Dakota; but, it must be kept in mind that most previous work in southeastern North Dakota was done before morphostratigraphy and ecostratigraphy were formally defined.

In many cases the surface ecostratigraphic units cannot be differentiated from each other on the basis of surface morphology; it is therefore necessary to demonstrate that a particular lithostratigraphic unit is responsible for a particular morphologic feature (Johnson, Gross, and Moran, 1971). Morphologic features that predate the latest glaciation may not show evidence on aerial photographs of having been overridden. If the interpretation of the glacial history of an area is based only on surface morphology, the interpretation will be in error if it is not known that the surface features have been overridden.

Palimpsest Topography

White (1962) demonstrated that most end moraines in northeastern Ohio owe neither their form nor most of their volume to the deposits of the last readvance of the ice sheet. Some of the end moraines there are composed of three or more tills of which the uppermost is only a few feet thick and forms a veneer over the end moraine (White, 1962). Thus, the end moraine predates the last advance. "The uppermost till is the last record, but earlier records below it may read much as a 'palimpsest' may be read from an ancient manuscript on which two or more writings are superimposed" (White, 1962, p. 73).

Surface geomorphic features may also reflect underlying bedrock topography. Glacial sediment may form a veneer over bedrock as in much of the Missouri Plateau (Figure 1). Palimpsest bedrock topography may therefore be misinterpreted as morainic topography.

This report will present evidence for a revision of previously interpreted ice margins. Where observed, the uppermost lithostratigraphic units cross three previously interpreted end moraines in southeastern North Dakota: the Luverne, the Oakes, and the Grace City End Moraines. The previous interpretations of each will be discussed separately.

The Luverne End Moraine

The Luverne End moraine is an irregularity in the surface of central Ransom County. It consists of a belt of small hills extending northwest to southeast across central Ransom County (Figure 2). The area of hills is 2 to 4 miles wide and about 10 miles long. It extends from about 4 miles west of Enderlin, in north-central Ransom County, to about 3 miles east of Hoving, in Sargent County. In Ransom County, the crests of the hills are less than 30 feet above the surrounding topography.

Previous interpretations

Todd (1896, p. 48) considered the "confused system of isolated knobs" to "mark the culmination of glacial activity" in central Ransom County. He concluded that the hills were part of a terminal moraine that extended from Valley City, in central Barnes County, to Lake Traverse, in northeastern South Dakota (Figure 2). He concluded that the moraine marked the border of a glacial lobe that flowed into Ransom County (Todd, 1896). He also observed, however, that the drift that forms the hills is not the same drift that forms the glacial topography west of the belt of hills (Todd, 1896).

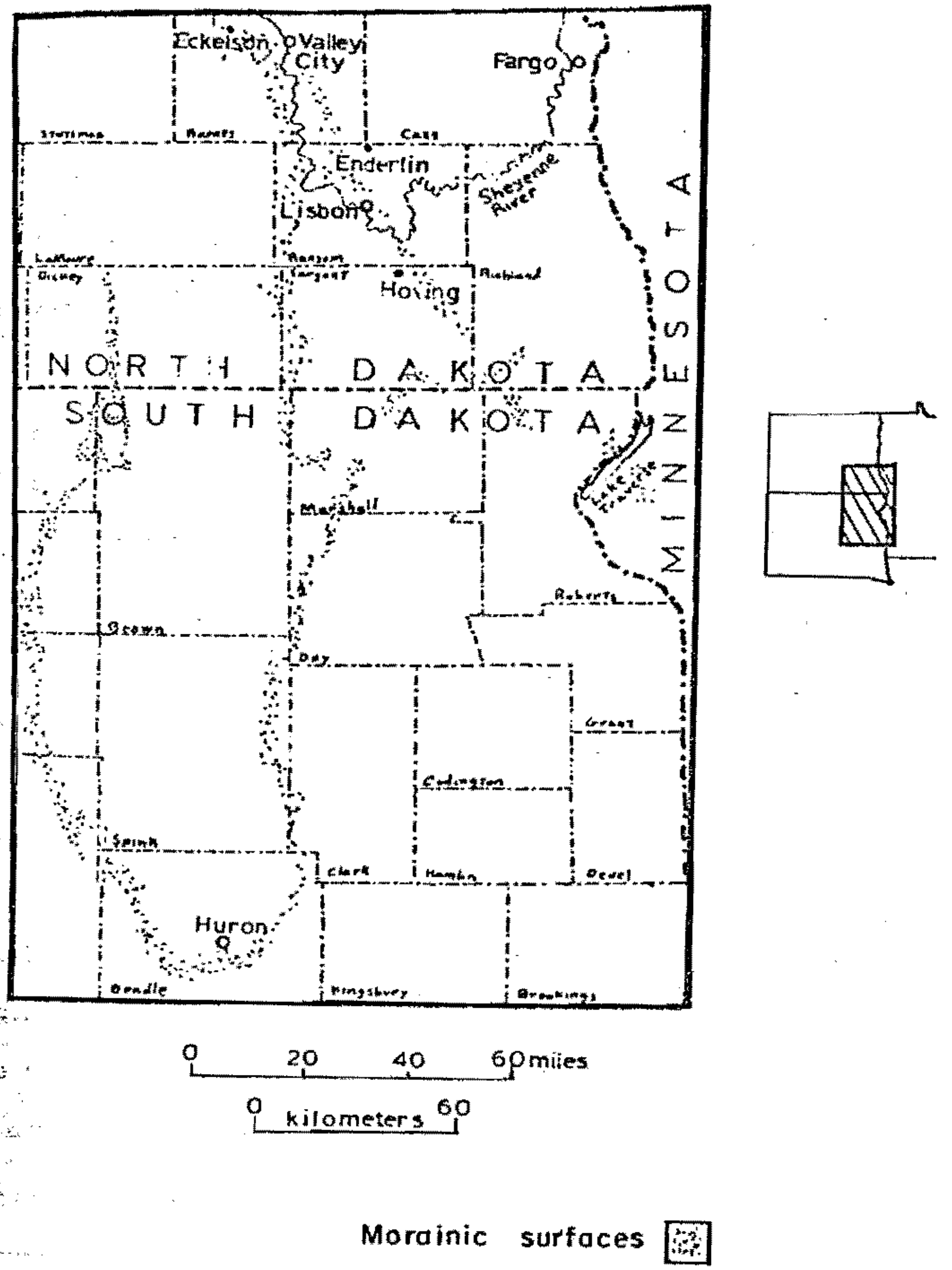

Fig. 2. Glacial Hills in Parts of North and South Dakota. Only the hills of the latest two terminal moraines are shown. Modified from Todd, 1896.

Recent workers (Colton, Lemke, and Lindvall, 1963; and Clayton, 1966) used newer methods to study the surficial geology of Ransom County. They based their interpretations on aerial photographs, field reconnaissance, and regional mapping studies.

Colton, Lemke, and Lindvall (1963) also mapped an area of hills in north-central Ransom County (Figure 3). The hills are 6 miles west of Enderlin and 3 miles east of the Sheyenne River in northwestern Ransom County and extend 6 miles south into Ransom County. The contact of the hilly region with the surrounding relatively flat region was mapped as either approximate or gradational (Colton, Lemke, and Lindvall, 1963). They considered this hilly region to be the southern edge of an end or marginal moraine which extends north into Barnes County (Figure 3). In northern Barnes County, the belt of hills was considered to mark the "outer limit of significant glacial advance," and is therefore an ecostratigraphic drift border (Colton, Lemke, and Lindvall, 1963).

Southeast of the belt of hills and south of the inferred drift border of Barnes County, Colton, Lemke, and Lindvall (1963) mapped an area of washboard moraines. The washboard moraines occupy T 135 N, R 56 W, and particularly T 134 N, R 55 W. Most of the washboard moraines extend northwest to southeast and individual ridges are concave to the northeast (Figure 3). Because washboard moraines indicate the direction of glacial flow, the ice which produced them is interpreted to have flowed from the northeast, the direction of concavity. Therefore, the washboard moraines and the Luverne End Moraine were presumably formed by the last readvance of ice into Ransom County. It was concluded that the Luverne End Moraine was formed by a glacier

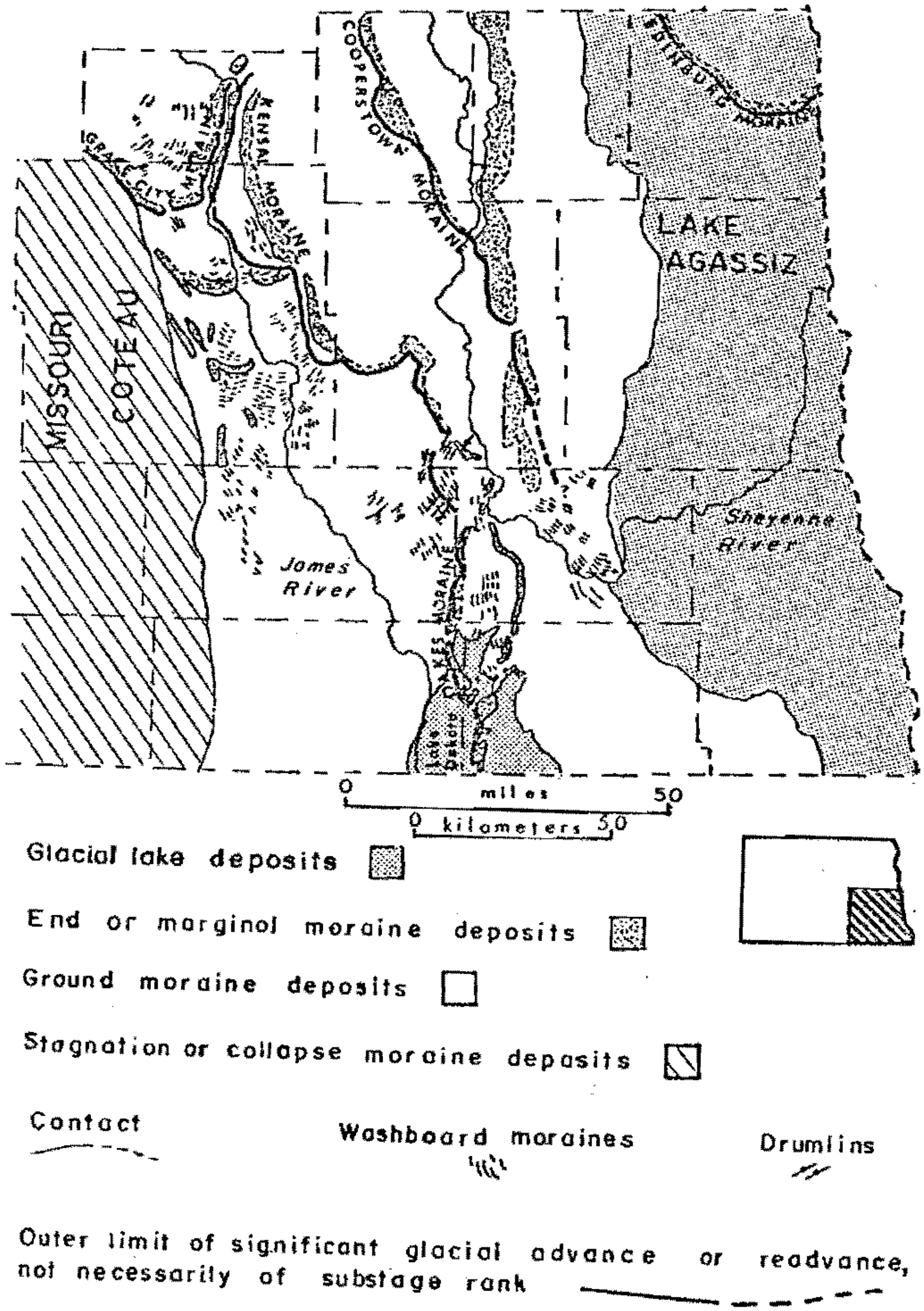

Fig. 3. Surficial Geology of Southeastern North Dakota. After Colton, Lemke, and Lindvall, 1963.

that advanced from the northeast (Figure 4) (Colton, Lemke, and Lindvall, 1963).

Block (1965) also mapped the hilly region in northern Barnes County where he recognized a long straight upland extending north-south through the center of that county (Figure 3). The upland is 1½ miles wide and extends 8 miles south from the Barnes-Griggs county line (Block, 1965). Block considered this ridge to be a terminal moraine. The crest and outer slope of the ridge are marked by numerous boulders and the long inner slope of the ridge descends to nearly flat ground moraine (Block, 1965). He named this region of hilly topography the Luverne End Moraine after the village of Luverne, which lies at the center of the ridge in Steele County. The Luverne Drift, an ecostratigraphic unit, forms the ridge and the ground moraine east of the ridge (Block, 1965).

In addition, Block analyzed the drift of this area. He concluded that the grain-size distribution and the carbonate content of the till of the Luverne Drift is identical to that of the drift west of the Luverne End Moraine (Block, 1965).

Clayton (1966) subsequently presented an interpretation of the sequence of glaciations of all of North Dakota, based on radiocarbon dates and previously mapped ice-margin positions. He then attempted to correlate radiocarbon dates from phases of Lake Agassiz with dates for surrounding regions. He identified all the named surface drifts as ecostratigraphic units (changed subsequently to event-stratigraphic units) of North Dakota and the corresponding ice margins of the glacier that deposited the drift. He concluded that the named surface drifts are lithologically indistinguishable on a regional scale.

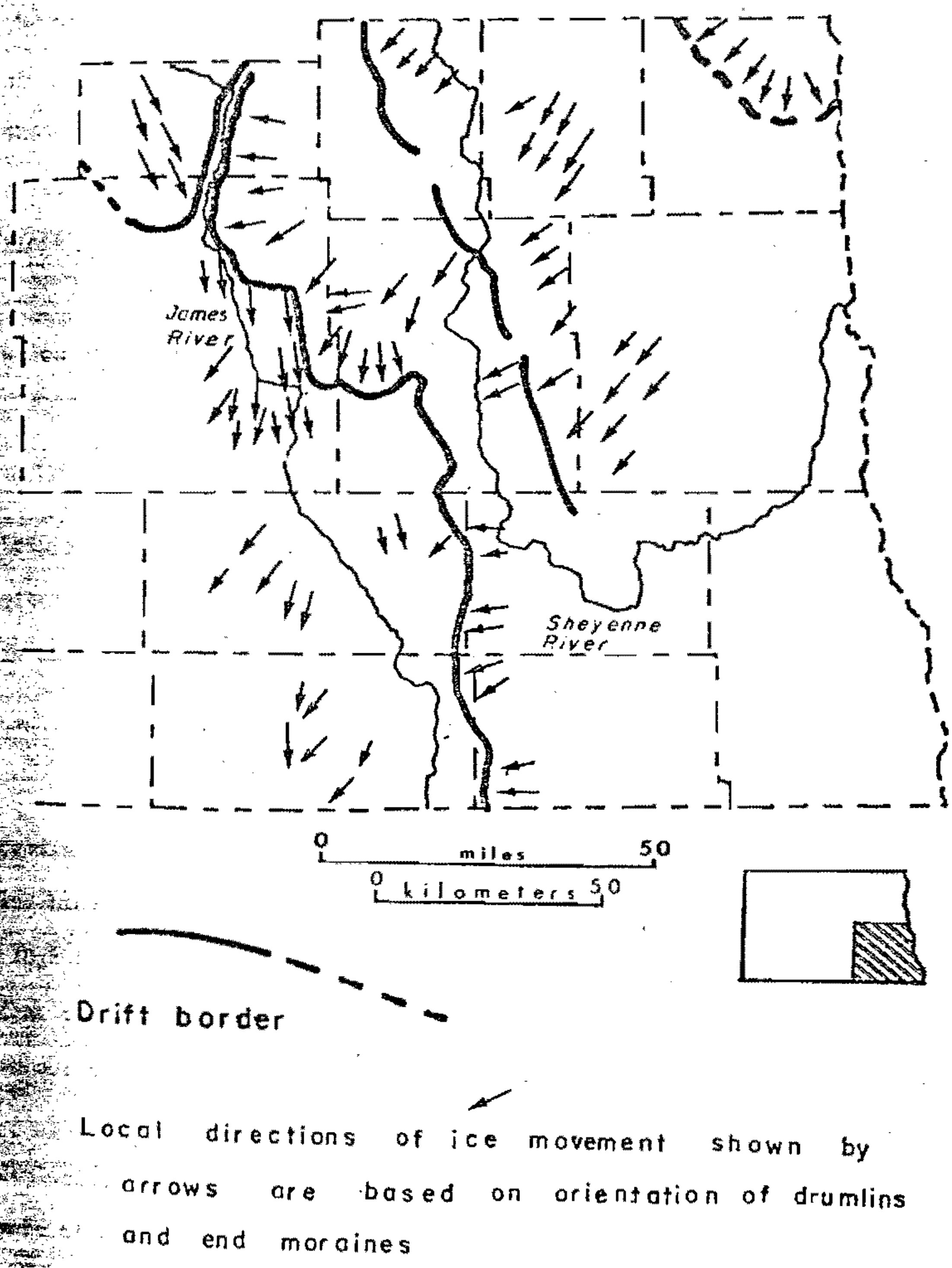

Fig. 4. Approximate Location of Known and Inferred Wisconsin Stage Drift Borders and Directions of Ice Movement Associated with Each Advance (Colton, Lemke, and Lindvall, 1963).

Clayton (1966) included the Luverne Drift in his summary, placing the western border of the Luverne Drift along a line about 3 miles west of Enderlin, southeast to Milnor in northeastern Sargent County (Figure 5). The end moraine of the Luverne Drift in Ransom County was recognized by tracing southward into Ransom County the Luverne End Moraine mapped by Block (1965) in northern Barnes County.

All of these researchers, then, identified a terminal moraine which subsequently was called the Luverne End Moraine.

The Oakes End Moraine

In my study area, a small ridge extends from northeastern LaMoure County to southwestern Ransom County (Figure 3). The ridge is about 28 miles long and generally less than a mile wide. The crest of the ridge is about 15 feet above the surrounding topography.

Previous interpretations

The ridge across western Ransom County was interpreted to be a terminal moraine by Todd (1896), Lemke and Colton (1958), Lemke, Colton, and Lindvall (1963), and by Clayton (1966). Hard (1929) believed the ridge to be a recessional moraine. The previous workers all concluded that this ridge is part of a large end moraine extending north-south across southeastern North Dakota (Figure 3).

Todd (1896) concluded that this ridge was formed during last deglaciation of western Ransom County. He believed that the ridge was part of a terminal moraine extending from Eckleson in west-central Barnes County to Huron, South Dakota (Figure 2). He assumed that the ridge marked a surface drift border. Therefore, the drift of the ridge

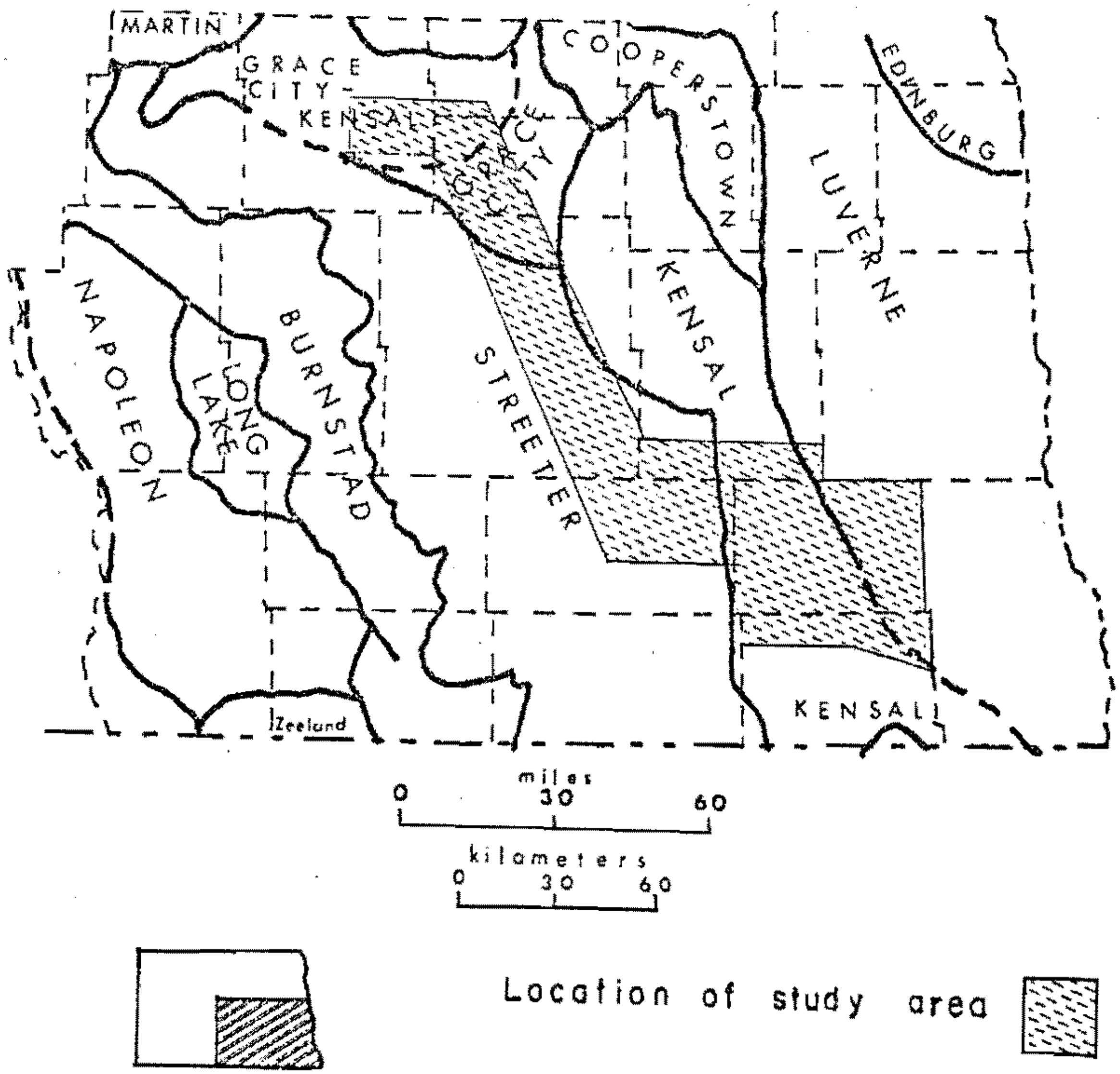

Fig. 5. Ecostratigraphic Drifts of Southeastern North Dakota (after Clayton, 1966).

and of the ground moraine east of the ridge would form the same eco-stratigraphic unit because the drift resulted from the same geologic event. The drift west of the ridge is an older unit which resulted from an earlier glaciation.

Hard (1929) named this ridge the Oakes End Moraine after the town of Oakes in southeastern Dickey County. He concluded that the Oakes End Moraine is a recessional moraine and therefore does not constitute a surface drift border. The moraine was presumably formed during a prolonged stillstand of a retreating glacier (Hard, 1929). According to him, the last stillstand of the glacier retreat from southeastern North Dakota is marked by this moraine (Hard, 1929).

Lemke and Colton (1958) considered the broad belt of hills about 3 miles wide in western Ransom County, extending from central Barnes County to southwestern Sargent County, to be the Oakes End Moraine (Figure 6). They concluded that the Oakes End Moraine was formed by a major readvance of the ice into southeastern North Dakota (Lemke and Colton, 1958).

According to them, the drift that forms the Oakes End Moraine and the adjacent ground moraine to the east is not present west of the ridge. An older drift, the Streeter Drift, extends west of the Oakes End Moraine (Lemke and Colton, 1958). The eastern border of the ground moraine associated with the Oakes End Moraine extends northwest to southeast in central Ransom County (Figure 6) (Lemke and Colton, 1958).

Colton, Lemke, and Lindvall (1963) considered the Oakes End Moraine to mark an outer limit of glacial advance. The advancing ice in Ransom County did not flow farther west than the Ransom-LaMoure

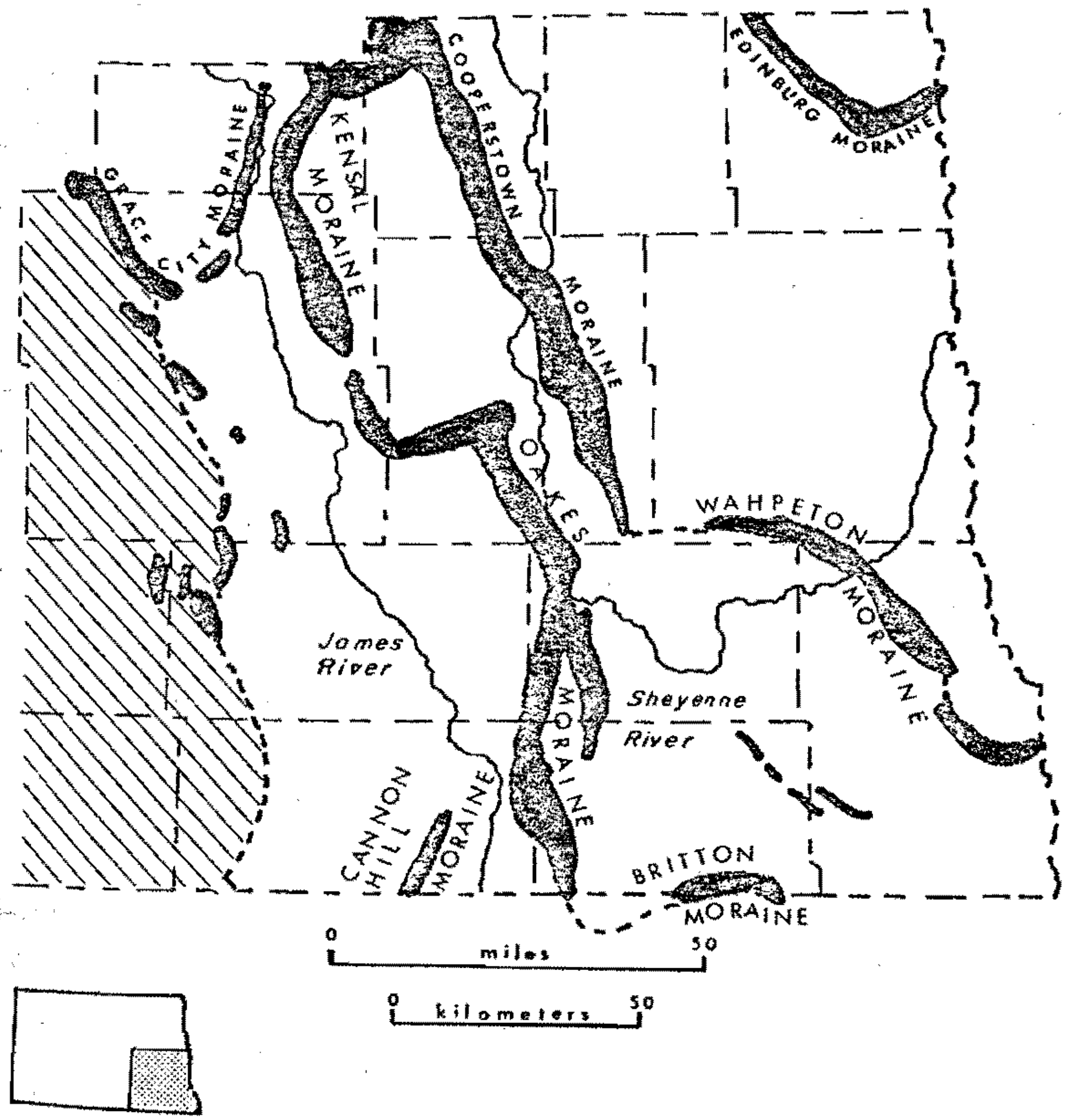

Fig. 6. Terminal Moraines of Southeastern North Dakota (after Lemke and Colton, 1958).

county line (Colton, Lemke, and Lindvall, 1963). The eastern border of the ground moraine associated with the Oakes End Moraine is mapped as the western border of the glacial Lake Agassiz plain in Ransom County (Figure 3).

Colton, Lemke, and Lindvall (1963) also recognized washboard moraines and drumlins less than a mile west of the Oakes End Moraine (T 136 N, R 59 W; and T 135 N, R 59 W) (Figure 3). The washboard moraine ridges are oriented northwest-southeast but show no concavity although some are slightly concave to the southwest. There are three drumlins in T 136 N, R 59 W. These are oriented northeast-southwest. These features were interpreted by Colton, Lemke, and Lindvall (1963) as indicating glacial flow from the northeast (Figure 4).

Numerous researchers therefore have interpreted the Oakes End Moraine as either a recessional moraine or as a terminal moraine. Only Hard (1929), who interpreted the ridge to be a recessional moraine, implied that the same drift is found on both sides of this ridge.

The Grace City End Moraine

In north-central Stutsman County, an arcuate ridge intersects my study area. The ridge extends from north-central Foster County and passes south of Edmunds in northern Stutsman County. The part of the ridge in Stutsman County is about 18 miles long and ranges in width from less than a mile to 3 miles. The crest of the ridge here is about 50 feet above the surrounding topography (Winters, 1963).

Previous interpretations

Lemke and Colton (1958) named the Grace City End Moraine after the town of Grace City in central Foster County. They concluded that the Grace City End Moraine was formed by a major readvance of the ice into Stutsman County. The trend of the Grace City End Moraine is different from the trend of end moraines of the previous advances of ice into southeastern North Dakota. The earlier Streeter End Moraine is oriented north-south and was presumably formed by a glacial advance from the east (Lemke and Colton, 1958). The orientation of the Grace City End Moraine and of numerous washboard moraines, concave to the northwest, suggests that the ice flowed as a sublobe from the northwest (Lemke and Colton, 1958) (Figure 4).

Lemke and Colton (1958) and, subsequently, Lemke, Colton, and Lindvall (1963) concluded that the Grace City End Moraine is a surface drift border marking the boundary of the Grace City Drift.

Winters (1963) stated that the Grace City End Moraine may be associated either with an ice margin that retreated from the southeast or it may mark the terminal position of a significant readvance of the ice sheet after its margin had retreated an unknown distance to the north. He added that the Grace City End Moraine does not exhibit well-developed morainal topography although the linear ridge of glacial drift was probably deposited primarily at the margin of an ice sheet. And, "local relief is greatest in the central and extreme west parts of the ridge, but rugged depositional topography is absent throughout much of the feature" (Winters, 1963, p. 58).

Clayton (1966) considered the Grace City End Moraine to be an ice margin representing a change in glacial regimen of at least minor significance. The ice margin that he described extends from Sheridan County to southwestern Sargent County (Figure 5). The Grace City, the

Kensal, and the Oakes End Moraines are part of this ice margin border (Figures 3 & 5) (Clayton, 1966).

Several researchers have therefore identified and described the Grace City End Moraine as either a recessional moraine or as marking a terminus of a significant glacial advance or readvance. This, plus the Oakes and Luverne End Moraines, must now be re-evaluated in the light of new information presented next.

DISCUSSION

Lithostratigraphy of the Glacial Sediment

Introduction

The use of lithostratigraphic units to define ecostratigraphic units must be done with care. One ecostratigraphic unit may constitute one or more lithostratigraphic units. For example, a glacial till plain and an outwash plain may constitute one ecostratigraphic unit if the till and the outwash gravel are deposits which resulted from the same glacial episode. But, because of typical differing lithologies, the till plain and the outwash gravels may be considered two different lithostratigraphic units.

In this discussion, I am assuming that each glacial event in the study area deposited a sediment that differs petrologically from the sediment of the previous glacial event. Therefore, if more than one glacial event deposited till having similar petrography and with a similar stratigraphic position, they would constitute one lithostratigraphic unit and the sediment would be misinterpreted as resulting from a single glacial episode. This problem, however, is not significant if it is assumed that the mechanisms of glacial erosion remain unchanged throughout an episode.

If the form and volume of a glacial feature are due to the latest glaciation, only one lithostratigraphic unit should constitute the ecostratigraphic unit for that feature. If the glacial feature were palimpsest, as in the casé of overridden features, two of more lithostratigraphic units might account for the form and volume of the feature.

Lithostratigraphy

Seven lithostratigraphic units are recognized in the glacial sediment of southeastern North Dakota (Table 1). Table 1 presents the grain-size distribution and the lithologic composition of the very-coarse-sand fraction of the till. The normalized crystalline value is the number of igneous and metamorphic fragments divided by the number of igneous and metamorphic fragments plus limestone and dolomite fragments. The lowermost unit, A, contains a relatively clayey till (the mean grain-size distribution is 29% sand, 43% silt, and 28% clay). The overlying unit, B, contains a silty-sand till (the mean grain-size distribution is 37% sand, 42% silt, and 21% clay). The very-coarse-sand fraction of the till of unit B also contains as much as 8% lignite. Unit C, which overlies unit B, contains a till that has a mean of 30% shale in the very-coarse-sand fraction. In the study area, unit C is the only unit divided into two subunits, an upper silty subunit and a lower sandy subunit. The overlying Gardar Formation (Hobbs, 1975) contains a till that has a mean of 65% shale in the very-coarse-sand fraction.

The till of the Dahlen Formation (Hobbs, 1975), found overlying the Gardar Formation, is lithologically similar to the till of unit B except that there are no lignite fragments. The Dahlen Formation is recognized mostly by its stratigraphic position. This formation contains the youngest of the till having such a high percentage of shale (45%) in the very-coarse-sand fraction. The Dahlen Formation lies

TABLE 1

GRAIN-SIZE DISTRIBUTION AND LITHOLOGIC COMPOSITION OF THE VERY-COARSE-SAND FRACTION OF THE GLACIAL SEDIMENT (TILL) IN THE STUDY AREA

Unit	% Sand	% Silt	% Clay	% Igneous & Metamorphic fragments	% Limestone & Dolomite fragments	% Shale	Normalized Crystalline Value
Unit E	34	43	23	67	23	10	0.74
Unit D	33	40	27	52	29	19	0.64
Dahlen Formation	30	43	27	31	25	44	0.55
Gardar Formation	22	49	29	19	16	65	0.54
Unit C	29	41	30	40	30	30	0.57
Unit B	37	42	21	29	23	48	0.56
Unit A	29	43	28	38	26	36	0.59

directly on the Gardar Formation and directly below unit D. The till of unit D has less shale than any other till in Ransom County; the very-coarse-sand fraction of the till contains a mean of 19% shale. Where observed in Stutsman and LaMoure Counties, the till of unit D contains more shale fragments and fewer igneous and metamorphic rock fragments than the till of the overlying unit E. The till of unit E, the youngest unit in the study area, contains fewer shale fragments than any other till in the study area, even unit D. The very-coarse-sand fraction of the till contains a mean of 10% shale fragments.

Extent

The lower three units, A, B, and C, are uncommon; they are recognized only in Ransom and northern Sargent County (Plates 3 through 7). The Gardar Formation is commonly found in exposures along the Sheyenne River in Ransom County; it is recognized at one outcrop in LaMoure County and at one outcrop in northern Sargent County. In my study area, the Gardar Formation is not found north of LaMoure County (Plates 3 through 8), although the formation is recognized outside my study area in northeastern North Dakota (Hobbs, 1975). The Dahlen Formation and unit D, however, are recognized throughout the study area (Plates 3 through 8). Unit E is not found east of LaMoure County (Plates 7 and 8).

Petrography

The petrography of a till often reveals the direction of transport of the till. If the source of the transported rock particles is known, it may be inferred that the glacier incorporated at least some of the rock fragments from the source area and the fragments were transported along the line of glacier flow. Thus, the petrography of the components of the till may be used as an indicator of glacial transport, particularly if the source area is close by.

Source areas

Figure 7 locates the source areas of the lithologic components of the very-coarse-sand fraction from the till units of southeastern North Dakota. The igneous and metamorphic rock fragments were derived from either the Canadian Shield or from the sandstone of western North Dakota. However, it is unlikely that the sandstone of western North Dakota contributed much very-coarse-sand to the till of southeastern North Dakota because of the additional evidence for a generally southerly flow of the ice sheets and because the sandstone of western North Dakota does not contain much coarse sand. The limestone and dolomite fragments were derived from the northern Red River Valley. Shale fragments were derived from the Cretaceous shale of eastern North Dakota.

Direction of transport

The direction of transport of the till of the Gardar Formation and of younger units may be inferred from the petrographic data; but, there is yet insufficient data on which to base an interpretation of the direction of transport of units older than the Gardar Formation.

Gardar and Dahlen Formations. The large amount of shale fragments in the very-coarse-sand fraction of the till of the Gardar and Dahlen Formations indicates that the contributing glacier advanced from the north or northeast into the study area over subcrops of Cretaceous shale, which forms the bedrock of the study area.

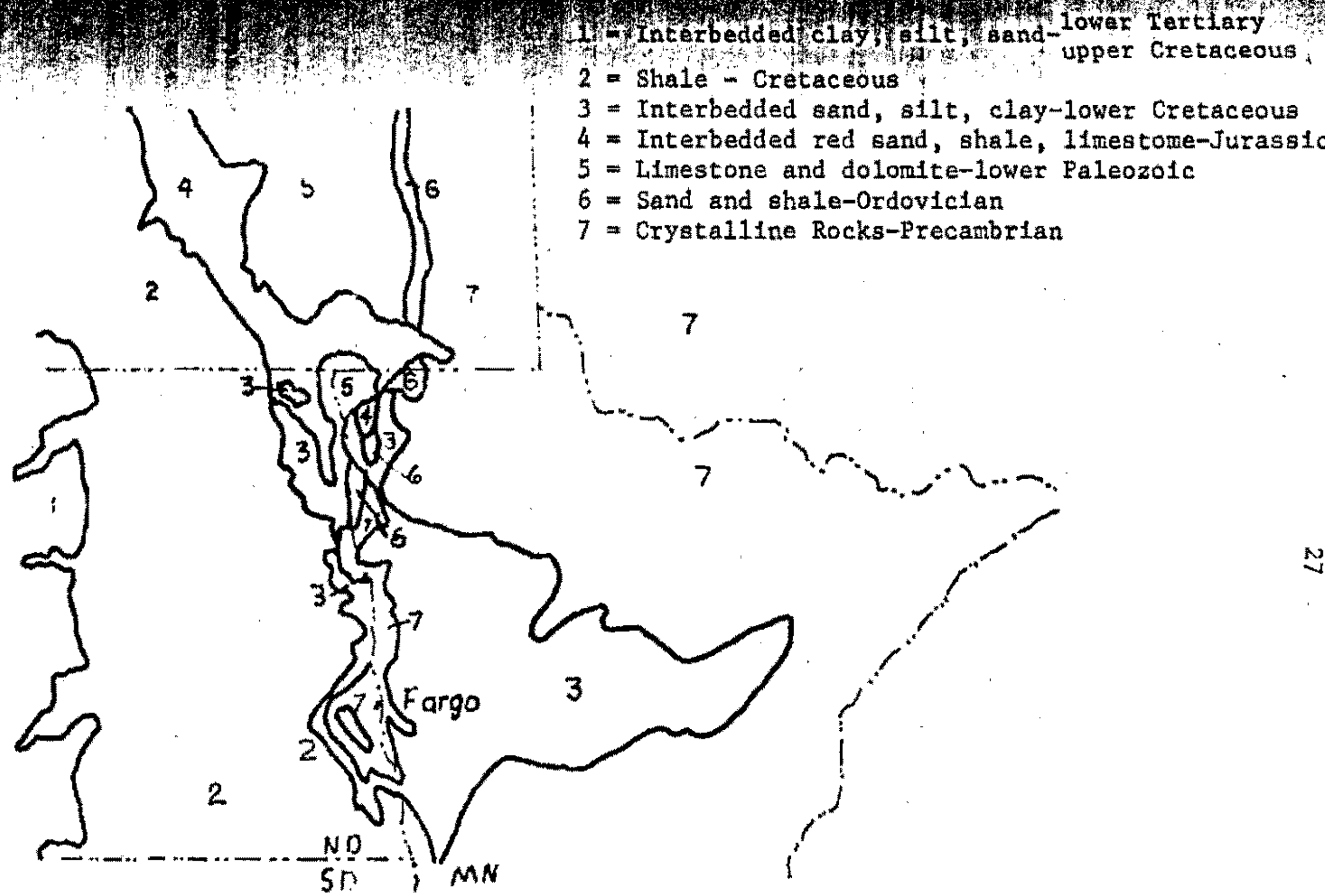

Fig. 7. Bedrock Geology of Eastern North Dakota, Northern Minnesota and Southeastern Manitoba (from Sackreiter, 1975).

Units D and E. The small amount of shale and the large amount of igneous and metamorphic rock fragments in the very-coarse-sand fraction of the till of units D and E indicates that the glacier that deposited the sediment of these units probably advanced from a generally northwesterly direction. The igneous and metamorphic rock fragments were probably derived from older glacial sediment rather than directly from the Canadian Shield to the northeast, because units D and E are absent in much of the eastern part of the study area and thicken to the west (Plates 3 through 8).

Areal change in the shale content

The areal change in the amount of shale in the very-coarse-sand fraction of the till was analyzed because the amount of shale in the till was the main criterion for correlating the units of glacial sediment and because the bedrock of the study area is shale (Figure 7). SYMAP plots of the shale percentages in the very-coarse-sand fraction of the till (Plates 10, 13, 16, 19, 22, 25, and 28) may reflect incorporation of bedrock material in the till; they could also reflect incorporation of unconsolidated substrate. Bedrock outcrops as well as substrate that were overridden at the time of glaciation should have influenced the petrography of the till deposited by the glacier. The change should be reflected particularly down-ice from the bedrock subcrop.

Gardar Formation. The areal change in the shale content of the till of the Gardar Formation, as well as the lithology, indicate a northerly origin for this unit (Plate 19). If compositional changes occur in the direction of transport, as is likely, then compositional isopleths may be considered equipotential lines for reconstruction of glacial flow lines (Gross and Moran, 1971).

The glacier that deposited the sediment of the Gardar Formation probably advanced from a northerly direction into the study area and incorporated an increasing amount of shale as the glacier flowed south. The isopleths of the shale percentage of the till of the Gardar Formation are concave to the north-northeast in the study area (Plate 19). The amount of shale in the till of the Gardar Formation increases east, south, and west from central Ransom County.

Pleistocene History of Southeastern North Dakota

If it can be assumed that each ecostratigraphic unit contains a lithostratigraphic unit discernible by the methods used in this study, then the interpretation of the Pleistocene history of southeastern North Dakota, based on the lithostratigraphy of the glacial sediment, revises previous ecostratigraphic interpretations. The following interpretations differ from previously accepted ones: (1) the Luverne End Moraine does not mark a lithostratigraphic border in either Ransom or Sargent Counties; (2) the Oakes End Moraine does not mark a surface drift border for any glacier which advanced from the northeast as was interpreted by Lemke and Colton (1958) and Colton, Lemke, and Lindvall (1963); (3) the Grace City End Moraine does not mark a surface drift border.

Luverne End Moraine

The lithostratigraphic interpretation of the extent of the surface drift of Ransom County implies that the Luverne End Moraine is not a terminal moraine because the surface lithostratigraphic unit east of the ridge, unit D, extends west into the subsurface of Stutsman and LaMoure Counties.

The Luverne End Moraine is not a palimpsest terminal moraine either, because all named lithostratigraphic units extend across the Luverne End Moraine.

However, if the sediment deposited as a result of the Luverne glaciation does not constitute a lithostratigraphic unit discernible by the methods used in this study, that is, the sediment is lithologically identical to the sediment of the prior glaciation, then my interpretation based on the lithostratigraphy is erroneous. The origin of the belt of hills in central Ransom County is therefore unknown.

Oakes End Moraine

If the sediment deposited as a result of the Oakes glaciation constitutes a lithostratigraphic unit discernible by the methods used in this study, the Oakes End Moraine does not mark a border of the surface drift of Ransom County, either, because the surface drift of Ransom County, unit D, extends west of the Oakes End Moraine (Plates 3 through 8).

If the Oakes End Moraine is still a recessional moraine, it does not mark the last recession of ice from Stutsman and LaMoure Counties because the surface drift of these counties, unit E, overlies unit D (Plates 7 and 8).

The Oakes End Moraine may, however, mark a surface drift border of unit E because unit E is not recognized east of the Oakes End

Moraine in LaMoure County.

However, the Oakes Drift, an ecostratigraphic unit, may not constitute a lithostratigraphic unit discernible by the methods used in this study. If this is the case, my interpretation of the ridge is wrong.

The origin of the Oakes End Moraine is unknown; but the ridge does not mark the border of the lithostratigraphic unit found east of the Oakes End Moraine.

Grace City End Moraine

If the sediment deposited as a result of the Grace City glaciation constitutes a lithostratigraphic unit discernible by the methods used in this study, The Grace City End Moraine does not mark a surface drift border in north-central Stutsman County. The surface drift north of the feature, unit E, is also found south of the ridge (Plate 8).

The Grace City End Moraine may, however, be a recessional moraine which would not make it a surface drift border; the till ridge may mark a stillstand in the retreat of the glacier that deposited unit E.

But, the Grace City Drift, an ecostratigraphic unit, may not constitute a lithostratigraphic unit discernible by the methods used in this study. The origin of the Grace City End Moraine is therefore unknown. The lithostratigraphy of the glacial sediment indicates that the till ridge does not mark a border of a lithostratigraphic unit.

Direction of Glacial Advances in Southeastern North Dakota

The interpretation of the direction of glacial advances in southeastern North Dakota, which is based on lithostratigraphic evidence, revises previously accepted ones. The surface lithostratigraphic unit of Ransom County and northern Sargent County was deposited by a glacier that advanced from a northwesterly direction and, where observed, the surface lithostratigraphic unit of Stutsman and LaMoure Counties was also deposited by a glacier that advanced from a northwesterly direction into the study area.

Ransom County and Northern Sargent County

Lemke and Colton (1958) and Colton, Lemke, and Lindvall (1963) indicated that the latest glacial advance in Ransom County and northern Sargent County came from a northeasterly direction (Figure 6). The petrography and extent of unit D, the surface lithostratigraphic unit of Ransom and northern Sargent County, indicate that the unit was actually deposited by a glacier that advanced from a northwesterly direction in the study area. The igneous and metamorphic rock fragments of the till of unit D presumably were largely derived from older glacial sediment. Unit D is extensive where observed in Stutsman and LaMoure Counties (Plates 7 and 8) and south and east of the subsurface bedrock ridge at the Ransom-LaMoure county line (Figure 8). However, in Ransom County, unit D occurs sporadically directly east of that bedrock ridge (Plates 3, 5, 6, and 7). Plates 3 through 7 show that unit D is thickest just south of the ridge at the Ransom-LaMoure county line (figure 8) and that the unit thins eastwardly until it is absent in northeastern

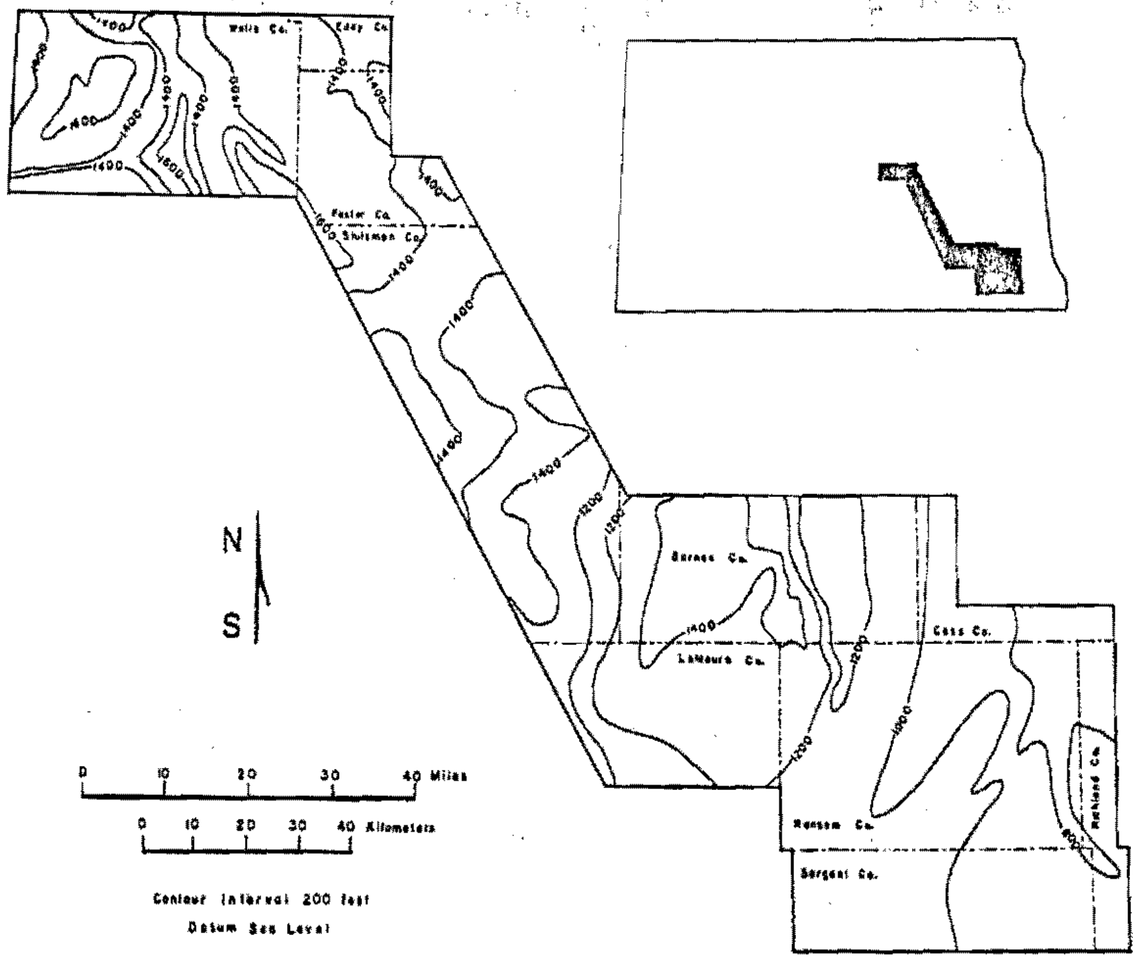

Fig. 8. Elevation of Bedrock Surface of the Study Area (after Bluemle, 1972 and Bluemle, in preparation).

Sargent County (Plate 4). The extent and thickness of unit D suggests that the glacier that deposited the sediment of the unit easily flowed around the southern tip of the bedrock ridge. The ice that flowed to the east over the ridge did not shear enough material to deposit a continuous layer of drift.

Therefore, on the basis of the petrography, extent, and thickness of the till of unit D, the glacier that deposited the sediment of the unit advanced from a northwesterly direction in the study area (Figure 9).

Stutsman and LaMoure Counties

Lemke and Colton (1958) and Colton, Lemke, and Lindvall (1963) indicated that the latest glacial advance in Stutsman and LaMoure Counties advanced from a northwesterly direction (Figure 4). The petrography and extent of unit E, the surface lithostratigraphic unit of Stutsman and LaMoure Counties, supports their interpretation. The igneous and metamorphic rock fragments were derived largely from older glacial sediment. Also, unit E is not recognized east of LaMoure County (Plates 7 and 8). Thus, the lithostratigraphic interpretation of the direction of the latest glacial advance in Stutsman and LaMoure Counties supports the ecostratigraphic interpretation (Figure 10).

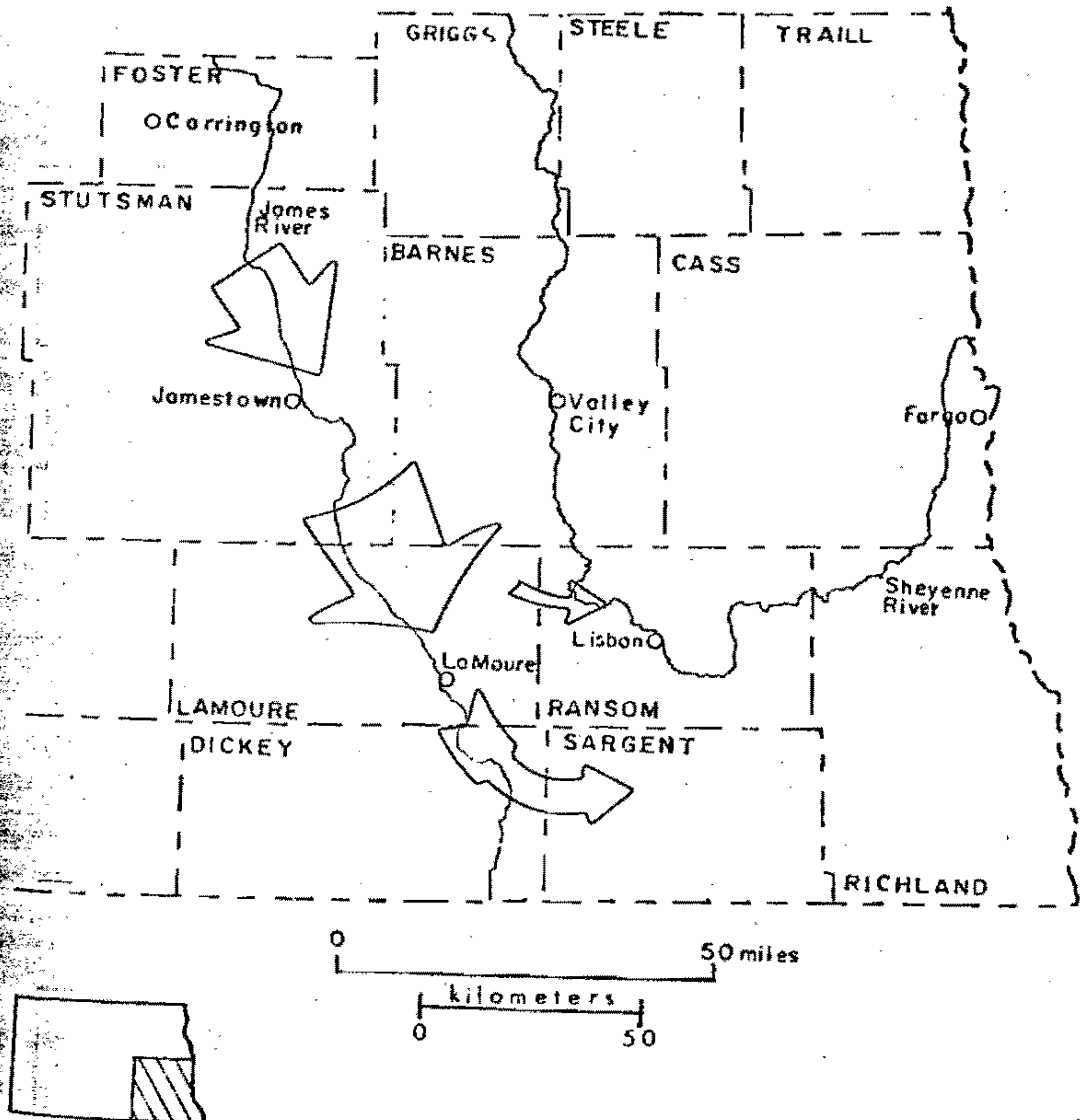

Fig. 9. Direction of Ice Movement Associated with Unit D.

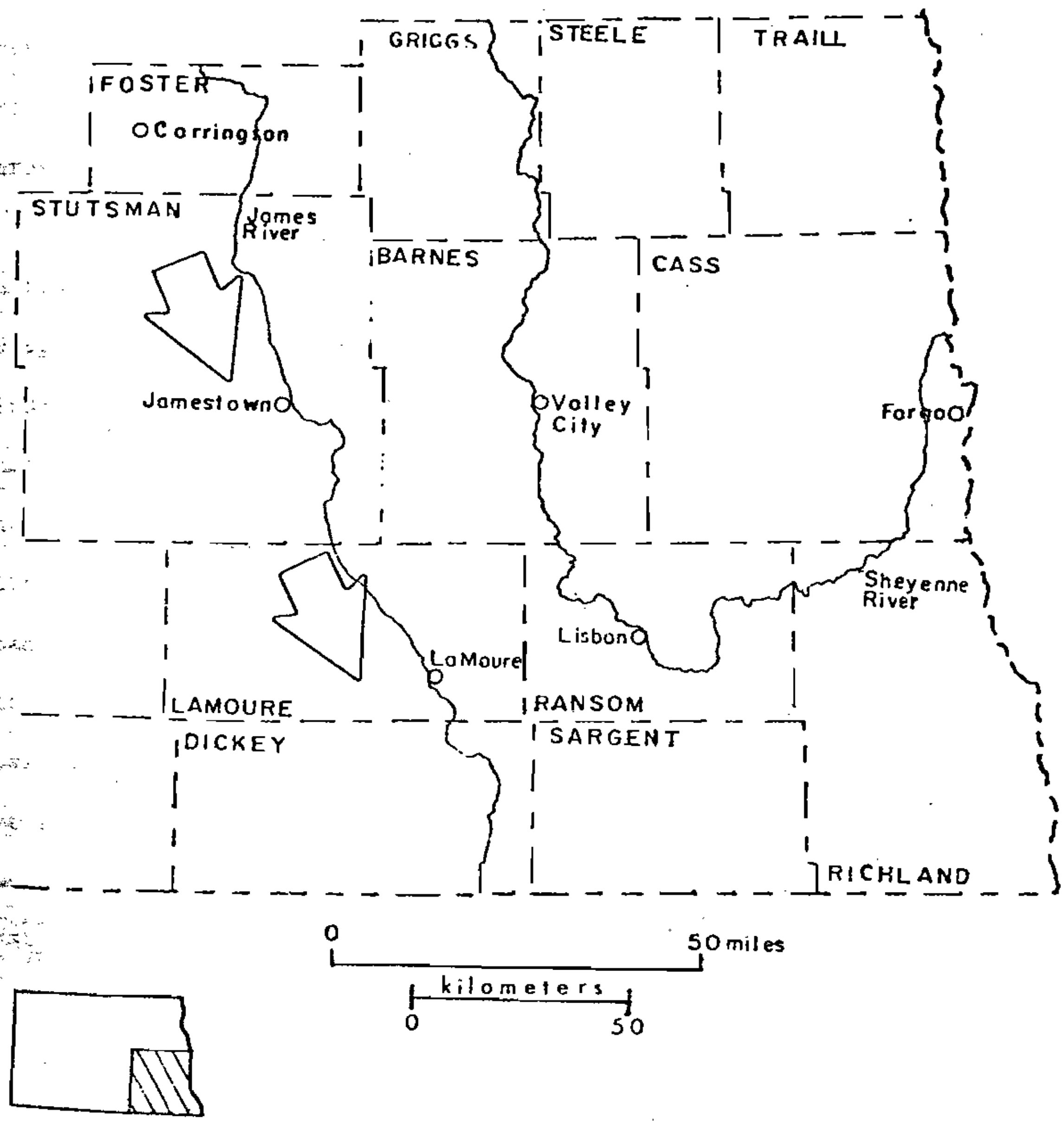

Fig. 10. Direction of Ice Movement Associated with Unit E.

SUMMARY

The Pleistocene history of southeastern North Dakota can be interpreted from the lithostratigraphy of the glacial sediment of the area. The lithostratigraphic framework developed in this study indicates numerous glaciations in the study area.

Previous interpretations of the Pleistocene history of southeastern North Dakota, based on ecostratigraphic units (Todd, 1896; Hard, 1929; Kresl, 1956; Lemke and Colton, 1958; Colton, Lemke, and Lindvall, 1963; Winters, 1963; Block, 1965; and Clayton, 1966), are revised by this study. If the ecostratigraphic units of southeastern North Dakota, the Luverne Drift, the Oakes Drift, and the Grace City Drift, constitute lithostratigraphic units discernible by the methods used in this study, then the Luverne and Grace City End Moraines do not mark surface drift borders because the surface lithostratigraphic drift extends beyond these positions. The Oakes End Moraine does not mark a surface drift border of the lithostratigraphic unit east of the end moraine position; the surface drift east of this supposed end moraine becomes a subsurface unit west of the Oakes End Moraine.

Recommendations

The Pleistocene history of an area should be developed on the basis of both morphology and lithology. The morphology should be analyzed for indicators of ice movement direction, and the lithostratigraphy of the glacial sediment should be analyzed to determine if the features pertain to the most recent glaciation or if the features are instead palimpsest.

Future research on the Pleistocene history of North Dakota should involve more work on the lithostratigraphy of the glacial sediment. More radiocarbon dates are needed in North Dakota. Lithologic data other than just the composition of the very-coarse-sand fraction should be used to differentiate the units of glacial sediment. The total lithostratigraphy of the glacial sediment from surface to bedrock should be analyzed on a regional scale before the Pleistocene history of an area is accepted.

APPENDIX A

RESEARCH METHODS

Sample Collection

During part of the summer of 1974, the North Dakota Geological Survey made a truck-mounted power auger available to me. Thirteen test-holes were drilled along the uplands of the Sheyenne River in Ransom County (Plate 1). The objective of this drilling program was to sample the uplands near Huff's surface sample locations to reassess his proposed lithostratigraphy. David Huff (Geology Department, University of North Dakota) analyzed the till of Ransom County during the summer of 1973. Sixteen auger borings were drilled along the uplands of the James River trench between Carrington and Jamestown (Plate 1) to investigate the lithostratigraphy of the glacial sediment of central North Dakota.

During part of the summer of 1975, I examined samples from test-holes drilled by the North Dakota State Water Commission in Ransom and Sargent Counties. I analyzed the grain-size distribution and the lithologic composition of the very-coarse-sand fraction of the till from the samples for which good electric log data (resistivity and spontaneous potential) were available. When the lithostratigraphy was essentially completed, I made non-standard pebble counts of till exposed along roadcuts and stream valleys in the Sheyenne River trench. The pebble counts were not standard because the pebbles were sieved out of the sediment and not picked out of the sediment as in a standard pebble count. Also, only 4 to 8 mm pebbles were analyzed. The objective of the pebble counts was to see if the predetermined units could be recognized in the field and to see if the lithologic composition of the very-coarse-sand fraction was the same as the lithologic composition of the small-pebble fraction.

In the second phase of my field work, I made a reconnaissance study to locate outcrops along the James River trench between Jamestown and the South Dakota Border. I then collected till samples from outcrops between Adrian and Grand Rapids (Plate 1). I again made non-standard pebble counts to see if I could recognize units in the field. Surface samples between Buchanan and Adrian (Plate 1) were taken with the assistance of Steve Moran (North Dakota Geological Survey) and Lee Clayton (Geology Department, University of North Dakota).

Sample Processing

The following field characteristics were described for all samples: grain-size distribution, grain petrography, Munsell color, structure (Soil Survey Staff, 1951), and the presence of sand masses or other unusual features such as boulder pavements. Initially, I analyzed the sample grain-size distribution using the standard North Dakota sieve and pipette methods (Moran, North Dakota Geological Survey, verbal communication, 1974); later, the method was changed to the sieve and hydrometer methods (Moran, North Dakota Geological Survey, verbal communication, 1974). I analyzed the grain-size distribution of about 550 samples.

The lithologic composition of the very-coarse-sand fraction (1 to 2 mm) was analyzed. The grains were identified according to whether they were igneous or metamorphic, limestone or dolomite, or shale. The ratio of the miscellaneous grains was calculated; the proportion of igneous and metamorphic grains, limestone and dolomite grains, and shale grains was then calculated, neglecting the miscellaneous grains. The normalized crystalline value, defined as the number of igneous and metamorphic grains divided by the sum of igneous and metamorphic grains plus limestone and dolomite grains, was also calculated. The average grain-size distribution, lithologic composition of the very-coarse-sand fraction, and normalized crystalline value were calculated for each unit.

Pebble Counts

During the summer of 1975, non-standard pebble counts were made at some outcrops in the study area to see if the units could be recognized in the field. Pebble counts were first made on till exposed at Huff's surface sample locations to see if known units could be recognized by the lithologic composition of the small pebble fraction of the till.

The pebble count procedure was long and tedious. A lunch bag (#6 paper sack) of till was taken to assure a count of at least fifty pebbles. This amount of sediment usually yielded over 100 small pebbles. The lunch bag was placed behind the left-rear sheel of my vehicle. I then drove back and forth over the bag until the sample was broken into small pieces about two cubic centimeters in size. In the field, the sediment was wet sieved through 16, 8, and 4 mm sieves. The lithologic composition of the small pebbles, 4 to 8 mm, was analyzed. The lithologic composition of the small pebble and very-coarse-sand fractions is shown in Table 2.

TABLE 2

LITHOLOGIC COMPOSITION OF THE PEBBLE AND VERY-COARSE-SAND FRACTIONS OF THE TILL OF SOME OF THE UNITS IN THE STUDY AREA

		Pebble Petrography			Sand Petrography				
Sample Site	Unit	% Igneous & Metamorphic Fragments	% Limestone & Dolomite Fragments	% Shale	% Igneous & Metamorphic Fragments	% Limestone & Dolomite Fragments	% Shale	Pebble Normalized Crystalline Value	Very-coarse-Sand Normalized Crystalline Value
N 2553	Unnamed	37	37	27	49	33	18	0.50	0.60
N 2555	Unnamed	28	51	22	50	30	21	0.35	0.63
N 2554	Unit D	10	36	54	49	27	23	0.22	0.64
N 2554	Unit D	27	30	43	58	27	15	0.34	0.57
N 2530	Unit D	36	50	14	55	28	16	0.42	0.66
N 2301	Dahlen	28	51	20	29	22	49	0.35	0.57
N 2531	Dahlen	11	30	59	26	22	52	0.27	0.54
N 2531	Dahlen	6	25	69	29	17	54	0.19	0.63
N 2533	Dahlen	9	31	60	26	24	50	0.23	0.43
N 2533	Dahlen	20	37	44	28	26	46	0.35	0.52
N 2553	Dahlen	20	30	50	33	20	47	0.40	0.62
N 1386	Gardar	12	30	58	16	12	72	0.29	0.57*
N 1386	Gardar	20	27	54	17	11	73	0.43	0.50*
N 2301	Gardar	18	24	65	11	17	72	0.43	0.39
N 2552	Gardar	11	20	69	23	16	61	0.35	0.54
N 10	Unit C	30	52	17	43	36	21	0.37	0.54*
N 2301	Unit C	17	50	33	31	33	36	0.25	0.48
N 2553	Unit C	23	49	28	28	36	37	0.32	0.44
N 10	Unit B	20	42	38	38	26	36	0.32	0.59*
N 2301	Unit B	21	26	53	28	22	50	0.45	0.56
N 2554	Unit B	20	39	40	38	29	33	0.47	0.68
N 2555	Unit A	22	27	51	40	24	36	0.45	0.63

*Huff's sample site.

The lithologic composition of the small pebble and the very-coarse-sand fraction was found not to be comparable. The lithologic composition of the two size fractions may differ for the following reasons: the pebbles of the till are more susceptible to weathering than are the very-coarse-sand fraction (Matsch, 1971); some shale pebbles become soft and mushy when wet while others remain firm; and the weathering of the till varies from outcrop to outcrop, some outcrops probably receive more rain than others and some outcrops are old exposures while others were fresh cuts no more than a few weeks old.

On the basis of these factors, I conclude that the lithologic composition of the small pebble fraction does not seem to be useful for distinguishing till units in the study area because the data are not consistent and the sieving process is too time consuming to do in the field. The lithologic composition of till can be quickly estimated in the field by close examination with a hand lens. Till units in this study area are best differentiated by a laboratory analysis of grain-size distribution and the lithologic composition of the very-coarse-sand fraction.

APPENDIX B

LITHOSTRATIGRAPHY

Introduction

Unnamed units are described first. The named units in the study area, units A through E, are described in stratigraphic order from the oldest (lowest correlable unit) to the youngest. Some of the units are not formally named because other work in progress will probably permit correlation with existing formations. There are no absolute age dates for any of the units described.

Unnamed Units

Unnamed units have no identifiable correlative unit in the study area. Some uncorrelated units are found at the base of testholes; others seem to be related to glacial shear blocks. All unnamed units are shown in the stratigraphic cross sections (Plates 3 through 8). The grain-size distribution, lithologic composition of the very-coarse-sand fraction, and the normalized crystalline value are shown for all units. The unnamed units are unpatterned in the cross sections.

The most extensive unnamed unit is in eastern Ransom County; this is the only unnamed unit that is recognized in more than one location. The unit is recognized in North Dakota State Water Commission testholes 9263, 9262, and 9261 (Plate 3). The unit is unnamed because its position in the stratigraphic sequence is unknown; it is older than unit B, but it may be older or younger than unit A. In testholes 9263 and 9262, the unit underlies unit B and overlies the Niobrara Formation. A layer of oxidized sand overlies this unnamed unit in testhole 9261. This oxidized sand may represent a buried weathered horizon. In testhole 9261, a thin unnamed unit lies between this more extensive unnamed unit and the Niobrara Formation. The thick unnamed unit in eastern Ransom County is sandy and has a relatively small amount of shale in the very-coarse-sand fraction. The amount of shale in this fraction of this unit ranges from 17% in testhole 9263 to 34% in testhole 9262. The normalized crystalline value ranges from 0.44 in testhole 9263 to 0.59 in testhole 9261. The grain-size distribution remains constant. From testhole 9263 to testhole 9262, the unit has the same grain-size distribution, stratigraphic position, and normalized crystalline value. From testhole 9262 to testhole 9261, the normalized crystalline value increases but the grain-size distribution, stratigraphic position, and the amount of shale remain the same.

Other unnamed units are found in the study area; however, these are mostly single samples and may represent either additional units or shear blocks.

Named Units

The following units contain till that can be traced considerable distances within or beyond the study area. The lower three units and the upper two units are not formally named and are not correlated with units outside the study area. Two formations in the study area, Gardar and Dahlen, were previously recognized in northeastern North Dakota (Hobbs, 1975).

Unit A

Reference sections. North Dakota State Water Commission testhole 9226 NE¼NW¼NW¼ sec 27 T 134 N R 58 W (Plate 5). North Dakota State Water Commission testhole 9258 SE¼SE¼SE¼ sec 2 T 132 N R 55 W (Plate 4).

Description. Unit A is exposed northeast of the town of Fort Ransom at sample site N-2555 (Plates 1 and 5). This exposure is at the bottom of a dirt road downhill from the Standing Rock Cemetery. The structure of the till is strong very-coarse prismatic to strong very-coarse block. Gray (5Y 6/1) clay skins cover the moist olive-brown (2.5Y 4/4) till. Dry, the oxidized till is light-olive-brown (2.5Y 5/4); the unoxidized till is gray (5Y 5/1). Manganese-oxide stain is common on many of the blocks and prisms. Lignite and spots of red ocher are conspicuous in the oxidized till. The lower contact is not exposed at site N-2555.

The grain-size distribution and the lithologic composition of the very-coarse-sand fraction of the till of unit A changes little throughout the study area (Plates 9 and 10). The average grain-size distribution of all samples of the till is 29% sand, 43% silt, and 28% clay. The mean lithologic composition of the very-coarse-sand fraction of all samples of the till is 38% igneous and metamorphic rock fragments, 26% limestone and dolomite fragments, and 36% shale fragments.

Differentiation. The till of unit A is differentiated from the till of other units on the basis of grain-size distribution, the lithologic composition of the very-coarse-sand fraction, and the stratigraphic position (Table 3). The till of unit A is relatively clayey with a moderate amount of shale in the very-coarse-sand fraction. Unit A contains

TABLE 3

CONTACTS, THICKNESS, AND RECOGNITION CRITERIA FOR UNIT A

Site Number	Plate	Thickness (feet)	Contacts		Recognition Criteria			
			Lower	Upper	Stratigraphic Position	Grain-Size Distribution	Very-Coarse-Sand Petrography	Other
9265	3	16	N/A	Unit B	X	X	X	None
9227	4 & 5	33	N/A	Unnamed		X	X	None
9258	4	16	Niob.*	N/A		X	X	None
N 2555	5	?	?	Unnamed		X	X	None
9226	5	10	Niob.*	Unit C		X	X	None
N 10	6	17	Niob.*	N/A	X	X	X	None

*Niobrara Formation

the only clayey till in the study area which contains lignite fragments. The sand content and the stratigraphic position are the bases for differentiating the till of unit A from the till of unit B. Unit B contains a relatively sandy lignitic till whereas unit A contains a relatively clayey lignitic till.

Unit B

Reference sections. North Dakota State Water Commission testhole 9262 SE¼SE¼SE¼ sec 2 T 134 N R 53 W (Plate 3). North Dakota State Water Commission testhole 9260 SE¼NE¼NE¼ sec 9 T 134 N R 53 W (Plate 3).

Description. Unit B is exposed at sample site N-2554 north and west of the town of Fort Ransom (Plate 1). This exposure is at the end of the road that extends along the western border of the Sheyenne River trench. The road passes up through the Pierre Formation, unit B, a thin layer of the Gardar Formation, and a thick section of unit D. Out of the valley, at the top of the road, there is a section of clay, silt, and sand above unit D.

At N-2554, the till of unit B is dark-grayish brown (2.5Y 4/2) when moist. The structure of the till is strong-medium-platy. Small pieces of lignite and red ocher are conspicuous although they occupy less than 1% of the exposed surface of the till. Sand lenses of different sizes are also present but not very common.

Unit B contains a silty-sand till; the mean grain-size distribution of all samples is 37% sand, 42% silt, and 21% clay. The mean lithologic composition of the very-coarse-sand fraction of all samples is 29% igneous and metamorphic fragments, 23% limestone and dolomite fragments, and 48% shale fragments. Dry, the unoxidized till is gray (5Y 5/1). Lignite is common in the till of unit B; in places the total very-coarse-sand fraction contains 8% lignite.

Differentiation. Unit B is differentiated from other units in the study area because this unit contains a silty-sandy lignitic till with a moderate shale content (40% to 50%). Stratigraphic position (Table 4) also differentiates unit B from other units.

Unit C

Reference section. North Dakota State Water Commission testhole 9260 SE¼NE¼NE¼ sec 9 T 132 N R 53 W (Plates 3 and 4).

Description. Unit C is divided into two subunits, an upper silty till subunit and a lower sandy till subunit. The lithologic composition of the very-coarse-sand fraction of these units is identical. Both the upper silty and the lower sandy subunits are recognized in the following testholes: 9261, 9265, and 9258.

The best exposure of unit C is at sample site N-2553 (Plates 1 and 6). This exposure is a roadcut through the south wall of the Sheyenne River trench. The lower sandy subunit of unit C, an overlying unnamed unit, and the Dahlen Formation are exposed here. The till of unit C, when moist, ranges from dark-grayish brown (2.5Y 4/2) to olive-brown (2.5Y 4/4) where oxidized; the moist unoxidized till is gray (5Y 5/1) to black (5Y 2/1). Because of the dark color of the till, limestone and dolomite fragments are easily seen. Abundant lenses of fine-grained sand give the till a sandy appearance. The till is pebbly and compact.

TABLE 4

CONTACTS, THICKNESS, AND RECOGNITION CRITERIA FOR UNIT B

Site Number	Plate	Thickness (feet)	Contacts Lower	Contacts Upper	Recognition Criteria: Stratigraphic Position	Grain-Size Distribution	Very-Coarse-Sand Petrography	Other
9265	3	9	Unit A	Unit C	X	X	X	None
9263	3	21	Unnamed	N/A		X	X	None
9262	3	61	Unnamed	Unit C	X	X	X	None
9260	3&4	46	Niob.*	Unit C	X	X	X	None
9255	3	44	Niob.*	N/A		X	X	None
9258	4	9	N/A	Unit C	X	X	X	None
9260	4	48	Niob.*	Unit C	X	X	X	None
N 2554	5	42	Pierre	Unit C	X	X	X	None
N 1392	6	?	?	Unit C	X	X	X	None
N 10	6	10	N/A	Unit C	X	X	X	None
N 2301	6	?	?	Unit C	X	X	X	None
9221	7	170	Pierre	N/A		X	X	None

*Niobrara Formation

At N-2553, the till of unit C has a strong coarse-prismatic structure. Manganese-oxide stain covers much of the prism surface of the till.

Differentiation. Unit C is differentiated from other units in the study area by the sparse amount of shale in the very-coarse-sand fraction of the till and by the stratigraphic position of the unit (Table 5). The till contains much less shale than units A or B or the overlying Gardar and Dahlen Formations. Unit C is the only unit in the study area that can be subdivided into two subunits, an upper silty subunit and a lower sandy subunit. In outcrop, unit C is the only unit with a till containing numerous sand and gravel lenses. Although relatively sandy, the till is compact and hard to dig when fresh.

Gardar Formation
(Hobbs, 1975)

Reference sections. Auger boring N-2705 NW¼NW¼NW¼ sec 7 T 135 N R 58 W (Plate 5). North Dakota State Water Commission testhole 9224 NE¼NE¼NE¼ sec 14 T 135 N R 58 W (Plate 5). Sample site N-2301 SE¼SW¼SE¼ sec 18 T 135 N R 56 W (Plate 6).

Description. The best exposure of the Gardar Formation in the study area is at sample site N-2301 (Plates 1 and 6). The till is exposed in a gully by a roadcut. The gully cuts through units B and C and the Gardar and Dahlen Formations. The till of the Gardar Formation is dark grayish-brown (2.5Y 4/2) when moist. The till is compact and pebbly; most of the pebbles are shale (Table 6). The till has a strong very-coarse prismatic structure. The prisms and pebbles are heavily stained with manganese oxide. A 2 to 3 inch bed of manganese-oxide

TABLE 5

CONTACTS, THICKNESS, AND RECOGNITION CRITERIA FOR UNIT C

						Recognition Criteria		
Number	Plate	Thickness (feet)	Contacts Lower	Contacts Upper	Strati-graphic Position	Grain-Size Distribution	Very-Coarse-Sand Petrography	Other
9265	3	97	Unit B	Dahlen	X	X	X	Silty & Sandy Subunits
9262	3	29	Unit B	Unnamed	X	X	X	Sandy Subunit
9261	3	55	Unit B	N/A	X	X	X	Silty & Sandy Subunits
9260	3&4	89	Unit B	Unit D	X	X	X	Silty Subunit
9258	4	41	Unit B	Unit D	X	X	X	Silty & Sandy Subunits
N 1390	5&7	?	?	Gardar	X	X	X	Sandy Subunit
N 2554	5	8	Unit B	Gardar	X	X	X	Sandy Subunit
9226	5	10	Unit A	N/A		X	X	Sandy Subunit
N 1392	6	3	Unit B	N/A	X	X	X	Sandy Subunit
N 2702	6	?	?	Gardar	X	X	X	Silty Subunit
N 2553	6	?	?	?		X	X	Sandy Subunit
N 10	6	25	Unit B	Gardar	X	X	X	Sandy Subunit
N 2712	6	?	?	Gardar	X	X	X	Sandy Subunit
N 2301	6	10	Unit B	Gardar	X	X	X	Sandy Subunit
N 2301	6	?	?	Gardar	X	X	X	Sandy Subunit
N 2704	6	?	?	Gardar	X	X	X	Sandy Subunit
N 2708	6	?	?	Gardar	X	X	X	Sandy Subunit
N 3501	N/A	?	?	Gardar	X	X	X	Silty Subunit

TABLE 6

CONTACTS, THICKNESS, AND RECOGNITION CRITERIA FOR THE GARDAR FORMATION

Site Number	Plate	Thickness (feet)	Contacts		Recognition Criteria			
			Lower	Upper	Stratigraphic Position	Grain-Size Distribution	Very-Coarse-Sand Petrography	Other
9262	3	25	Unnamed	Dahlen	X		X	None
9222	5,6,&7	15	Niob.*	Dahlen	X	X	X	None
N 1390	5&7	95	Unit C	Dahlen	X	X	X	None
N 2700	5&6	?	?	Dahlen	X	X	X	None
N 2554	5	?	Unit C	?	X	X	X	None
N 2705	5	?	?	Unit D		X	X	None
N 1386	5	?	?	N/A		X	X	None
9224	5	77	Niob.*	Dahlen	X	X	X	None
N 1388	6	?	?	N/A		X	X	None
N 2552	6	10	Pierre	N/A		X	X	None
N 1385	6	3	N/A	Dahlen	X	X	X	None
N 1392	6	24	N/A	Dahlen	X	X	X	None
N 2702	6	16	Unit C	Unnamed	X	X	X	None
N 10	6	5	Unit C	N/A	X	X	X	None
N 2712	6	10	Unit C	N/A	X	X	X	None
N 2701	6	?	?	Dahlen	X	X	X	None
N 2301	6	11	Unit C	Dahlen	X	X	X	None
N 2704	6	40	Unit C	Dahlen	X	X	X	None
N 2708	6	20	N/A	Dahlen	X	X	X	None
N 1391	7	?	?	N/A		X	X	None
N 2553	8	?	?	Dahlen	X	X	X	Boulder pavement
N 3501	N/A	8	Unit C	?	X	X	X	None
N 3503	N/A	?	?	?		X	X	None
N 3504	N/A	?	?	?		X	X	None
N 48	N/A	?	?	?		X	X	None

*Niobrara Formation

cemented gravel, so well cemented that it resembles highway pavement, marks the upper contact of the Gardar Formation.

The till of the Gardar Formation contains abundant shale. The mean lithologic composition of the very-coarse-sand fraction of all samples is 19% igneous and metamorphic grains, 16% limestone and dolomite grains, and 65% shale grains. The mean grain-size distribution of all samples is 22% sand, 49% silt, and 29% clay. The unoxidized till is gray (5Y 5/1) when dry. The till is pebbly and has a relatively large amount of very-coarse-sand.

Differentiation. The till of the Gardar Formation has a higher shale content than any other till in the study area, 65% in the very-coarse-sand fraction. The high silt and clay content distinguishes the till of this formation from the till of units B and of the Dahlen Formation (Table 6), the only other units in the study area with a till whose shale content is greater than 40% in the very-coarse-sand fraction.

Dahlen Formation
(Hobbs, 1975)

Reference sections. North Dakota State Water Commission testhole 9224 NE¼NE¼NE¼ sec 14 T 135 N R 58 W (Plate 5). North Dakota State Water Commission testhole 9181 NW¼NW¼NW¼ sec 10 T 136 N R 63 W (Plate 7).

Description. In Ransom County, sample sites N-2553 and N-2301 have good exposures of the Dahlen Formation (Plates 1 and 6). In LaMoure County, N-2553 is the best exposure of the Dahlen Formation (Plates 1 and 8).

Sample site N-2553 is a road cut through the south wall of the Sheyenne River trench (Plates 1 and 6). The till has a strong coarse-prismatic structure and the blocks of the till are lightly stained with iron-oxide. The till is easy to dig; cobbles and boulders are rare but pebbles are common. Most of the pebbles are shale (Table 2) but, because of the dark color of the till, the limestone and dolomite pebbles appear more abundant. The bottom contact of the unit can be seen on the east side of the roadcut at sample site N-2553. At the base of the unit here, there is a 2 inch bed of massive red clay. A 10 foot bed of fine grained oxidized sand lies below the red clay bed.

Three miles east, the formation is exposed at sample site N-2301 (Plates 1 and 6). Here, the formation is exposed in a gully by a road-cut. The formation here is olive-gray (5Y 5/2) when moist. The till has a strong medium-platy structure. Small sand lenses are more common at this sample site than at N-2533. Pebbles are abundant here, especially limestone and dolomite pebbles (Table 2). Boulders and cobbles are rare here, though. There is no iron-oxide stain of the till at this outcrop.

At sample site N-2533, in LaMoure County (Plates 1 and 8) the Dahlen Formation rests on a soled boulder pavement that marks the top of the Gardar Formation. Here, the Dahlen Formation has a strong medium-platy structure. Cobbles and boulders are rare but pebbles are common. The till is lightly stained with manganese-oxide. Sand lenses are common but not abundant.

Differentiation. The shale content of the till of the Dahlen Formation is higher than that of the till above but lower than that of the till of the Gardar Formation. The till of the Dahlen Formation is sandier, contains fewer grains of limestone, dolomite, and shale than does the till of unit C. The grain-size distribution and the lithologic composition of the very-coarse-sand fraction are similar to that of the till of units B and A, but the till of the Dahlen Formation does not contain lignite. Stratigraphic position is the main criterion for distinguishing the till of the Dahlen Formation from the till of units older than the Gardar Formation (Table 7).

Age and correlation. The Dahlen Formation was formed during the main Late Wisconsinan glaciation (Hobbs, 1975). Hobbs correlated the Dahlen Formation with the upper part of the Red Lake Falls Formation (Harris and others, 1974). Anderson (1976) correlated the upper part of the upper Red Lake Falls Formation with the New Ulm till (Matsch, 1971) and with the Dunvilla Formation of west-central Minnesota.

Unit D

Reference sections. North Dakota State Water Commission testhole 9183 SE¼SE¼SE¼ sec 6 T 136 N R 62 W (Plate 7). Sample site N-2554 SW¼SE¼NE¼ sec 35 T 135 N R 58 W (Plate 5).

Description. In Ransom County, the best exposure of unit D is at sample site N-2554 (Plates 1 and 5). The exposure is at the end of the road that extends along the western border of the Sheyenne River trench. The till of unit D here is olive (5Y 5/3) when moist, is

TABLE 7

CONTACTS, THICKNESS, AND RECOGNITION CRITERIA FOR THE DAHLEN FORMATION

Site Number	Plate	Thickness (feet)	Contacts Lower	Contacts Upper	Recognition Criteria: Stratigraphic Position	Grain-Size Distribution	Very-Coarse-Sand Petrography	Other
9265	3	14	Unit C	N/A		X	X	None
9262	3	19	Gardar	N/A	X	X	X	None
9261	3	35	N/A	N/A		X	X	None
9260	3&4	12	Unit C	N/A		X	X	None
9255	3	6	N/A	N/A		X	X	None
9227	4&5	52	N/A	Unit D	X	X	X	None
9222	5,6,&7	23	Gardar	N/A	X		X	None
N 1390	5&7	9	Gardar	N/A	X	X	X	None
N 2700	5&6	17	Gardar	N/A	X		X	None
9224	5	50	Gardar	N/A	X	X	X	None
N 1387	6	?	?	N/A		X	X	None
N 11	6	8	Niob.*	Unit D	X	X	X	None
N 1385	6	4	Gardar	Unit D	X	X	X	None
N 1392	6	10	Gardar	N/A	X	X	X	None
N 2702	6	25	Unnamed	N/A	X	X	X	None
N 2553	6	20	N/A	N/A		X	X	None
N 2712	6	6	Gardar	Unit D	X	X	X	None
N 2701	6	19	Gardar	Unit D	X	X	X	None
N 2301	6	7	Gardar	Unit D	X	X	X	None
N 2704	6	18	Gardar	N/A	X	X	X	None
9181	7	50	N/A	Unit D	X	X	X	None
9183	7	87	N/A	Unit D	X	X	X	None
9186	7	15	Pierre	Unit D	X	X	X	None
9187	7	77	Pierre	Unit D	X	X	X	None
N 1935	8	5	N/A	Unit D	X	X	X	None
N 2714	8	?	N/A	Unnamed		X	X	None

TABLE 7--Continued

Site Number	Plate	Thickness (feet)	Contacts Lower	Contacts Upper	Recognition Criteria Stratigraphic Position	Grain-Size Distribution	Very-Coarse-Sand Petrography	Other
N 1949	8	?	?	Unit D	X	X	X	None
N 1934	8	?	?	Unnamed	X	X	X	None
N 3076	8	?	?	Unit E	X	X	X	None
N 3077	8	?	?	Unit E		X	X	None
N 3078	8	38	N/A	Unit D	X	X	X	None
N 2531	8	?	?	Unit D	X	X	X	None
N 2533	8	30	Gardar	N/A	X	X	X	Boulder pavement
N 2534	8	?	?	Unit D	X	X	X	None
N 3502	N/A	?	?	?		X	X	None
N 3505	N/A	?	?	Unit D	X	X	X	None

*Niobrara Formation

pebbly, somewhat sandy and is easy to dig. There is no structure developed in the till at this outcrop.

In LaMoure County, unit D is exposed south of Adrian at sample site N-2532 (Plates 1 and 8). The exposure is a gully alongside a road that passes over an earth-filled dam. The most notable characteristic of the till of unit D here is the strong coarse-angular to subangular-blocky structure. The till of unit D here is gray (5Y 5/2) when moist; the clay skins are grayish brown (2.5Y 5/2). At this site, the till of unit D feels relatively clayey when compared to the till of the overlying unit E.

The till of unit D contains little shale in the very-coarse-sand fraction. The mean lithologic composition of the very-coarse-sand fraction of all samples is 52% igneous and metamorphic fragments, 29% limestone and dolomite fragments, and 19% shale fragments. The mean grain-size distribution of all samples is 33% sand, 40% silt, and 27% clay.

Differentiation. The till of unit D has the lowest shale content of all the tills in Ransom County and northern Sargent County. The till of unit D contains more shale grains and fewer igneous and metamorphic grains than the till of unit E. Stratigraphic position also is used to differentiate the till of unit D from the till of other units (Table 8).

Unit E

Reference sections. North Dakota State Water Commission testhole 9186 SE¼SE¼SE¼ sec 4 T 134 N R 61 W (Plate 8). Sample site N-2534 NE¼NE¼NE¼ sec 4 T 134 N R 61 W (Plate 8).

TABLE 8

CONTACTS, THICKNESS, AND RECOGNITION CRITERIA FOR UNIT D

Site Number	Plate	Thickness (feet)	Contacts		Recognition Criteria			
			Lower	Upper	Stratigraphic Position	Grain-Size Distribution	Very-Coarse-Sand Petrography	Other
9227	4&5	40	Dahlen	N/A	X	X	X	None
9258	4	57	Unit C	N/A		X	X	None
N 2554	5	?	?	N/A		X	X	None
N 2705	5	22	Gardar	N/A	X	X	X	None
N 11	5	12	Dahlen	N/A	X	X	X	None
N 1385	6	9	Dahlen	N/A	X	X	X	None
N 2712	6	5	Dahlen	N/A	X	X	X	None
N 2707	6	?	?	N/A		X	X	None
9181	7	30	Dahlen	Unit E	X	X	X	None
9183	7	50	Dahlen	Unit E	X	X	X	None
9186	7	10	Dahlen	Unit E	X	X	X	None
9187	7	27	Dahlen	N/A	X	X	X	None
N 1935	8	6	Dahlen	N/A	X	X	X	None
N 1937	8	?	?	Unit E	X	X	X	None
N 1944	8	?	?	Unit E	X	X	X	None
N 1942	8	?	?	Unit E	X	X	X	None
N 1945	8	?	?	N/A	X	X	X	None
N 2713	8	?	?	Unit E	X	X	X	None
N 3080	8	?	?	Unit E	X	X	X	None
N 1949	8	?	Dahlen	N/A	X	X	X	None
N 1934	8	4	Unnamed	N/A	X	X	X	None
N 3078	8	30	Dahlen	Unit E	X	X	X	None
N 2531	8	52	Dahlen	N/A	X	X	X	None
N 2532	8	?	?	Unit E	X	X	X	None
N 2534	8	25	Dahlen	Unit E	X	X	X	None
N 3505	N/A	?	Dahlen	?	X	X	X	None

Description. The best exposure of unit E is east of Grand Rapids at sample site N-2534 (Plates 1 and 8). The outcrop is near a road that cuts through the Dahlen Formation, unit D, and unit E (Plate 8). At the top of the roadcut, unit E lies beneath a 10 foot layer of very-fine-grained sand. The moist till is dark grayish brown (2.5Y 5/4) and feels sandy; the till of unit E is not very pebbly. The structure of the till here ranges from moderate medium-platy to moderate subangular-blocky. Because of the dark color of the till, fragments of igneous and metamorphic rock are easily seen.

The till of unit E has little shale. The mean lithologic composition of the very-coarse-sand fraction of all samples is 67% igneous and metamorphic fragments, 23% limestone and dolomite fragments, and 10% shale fragments. The mean grain-size distribution of all samples is 34% sand, 43% silt, and 23% clay. Dry, the till is light gray (2.5Y 7/2) where oxidized and gray (5Y 5/1) where unoxidized.

Differentiation. The unit is differentiated from other units by the scarcity of shale and by the sand content of the till of unit E. The till of unit E contains less shale than any other till in the study area. Stratigraphic position (Table 9) is used to differentiate unit E from other units.

TABLE 9

CONTACTS, THICKNESS, AND RECOGNITION CRITERIA FOR UNIT E

Site Number	Plate	Thickness (feet)	Contacts Lower	Contacts Upper	Recognition Criteria: Stratigraphic Position	Recognition Criteria: Grain-Size Distribution	Recognition Criteria: Very-Coarse-Sand Petrography	Recognition Criteria: Other
9181	7	21	Unit D	N/A	X	X	X	None
9183	7	10	Unit D	N/A	X	X	X	None
9186	7	32	Unit D	N/A	X	X	X	None
N 18	8	?	?	N/A		X	X	None
N 17	8	?	?	N/A		X	X	None
N 21	8	?	?	N/A		X	X	None
N 20	8	?	?	N/A		X	X	None
N 1936	8	7	N/A	N/A		X	X	None
N 1937	8	15	Unit D	N/A	X	X	X	None
N 1944	8	10	Unit D	N/A	X	X	X	None
N 1942	8	5	Unit D	N/A	X	X	X	None
N 1945	8	6	N/A	N/A	X	X	X	None
N 1948	8	?	N/A	N/A		X	X	None
N 2713	8	14	Unit D	N/A	X	X	X	None
N 3080	8	25	Unit D	N/A	X	X	X	None
N 1949	8	7	Dahlen	N/A		X	X	None
N 1947	8	15	Unnamed	N/A		X	X	None
N 1938	8	5	Unnamed	N/A		X	X	None
N 3076	8	40	Dahlen	N/A		X	X	None
N 3077	8	10	Unit D	N/A		X	X	None
N 3078	8	25	Unit D	N/A	X	X	X	None
N 2532	8	35	Unit D	N/A	X	X	X	None
N 2534	8	35	Unit D	N/A	X	X	X	None
N 3506	N/A	?	?	?		X	X	None
N 3507	N/A	?	?	?		X	X	None

APPENDIX C

EXPLANATION OF MAPS AND CROSS SECTIONS

Plate 1 shows the location of all samples used in this study. Plate 2 shows the locations of the cross sections, Plates 3 through 8. On Plate 2, the various cross sections are differentiated by varying line widths.

Plates 3 through 8 are stratigraphic cross sections. All named units are patterned in the cross sections; unnamed units are unpatterned. The darkness of the pattern corresponds to the amount of shale in the till of the unit.

Plates 9 through 29 are SYMAP plots, computer-generated maps, of the unit substrate and lithologic data of the till of the unit. The location of the data point is shown on the SYMAP plots. The value of the data point corresponds to the level shown in the frequency distribution, histogram, at the base of each map.

The substrate topography is the elevation of the lower contact of the unit. The maps of the areal change of the amounts of sand and shale may indicate lithologic changes in the direction of glacial flow.

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PLATE 8 STRATIGRAPHIC CROSS SECTION FROM HURDSFIELD TO GRAND RAPIDS

UNIT E

	% Sand	% Silt	% Clay	% Igneous & Metamorphic fragments	% Limestone & Dolomite fragments	% Shale	Normalized Crystalline Value
Mean	33	43	24	69	22	7	0.77
Standard Deviation	3	3	4	7	5	4	0.06
Variance	8	9	12	44	27	18	0

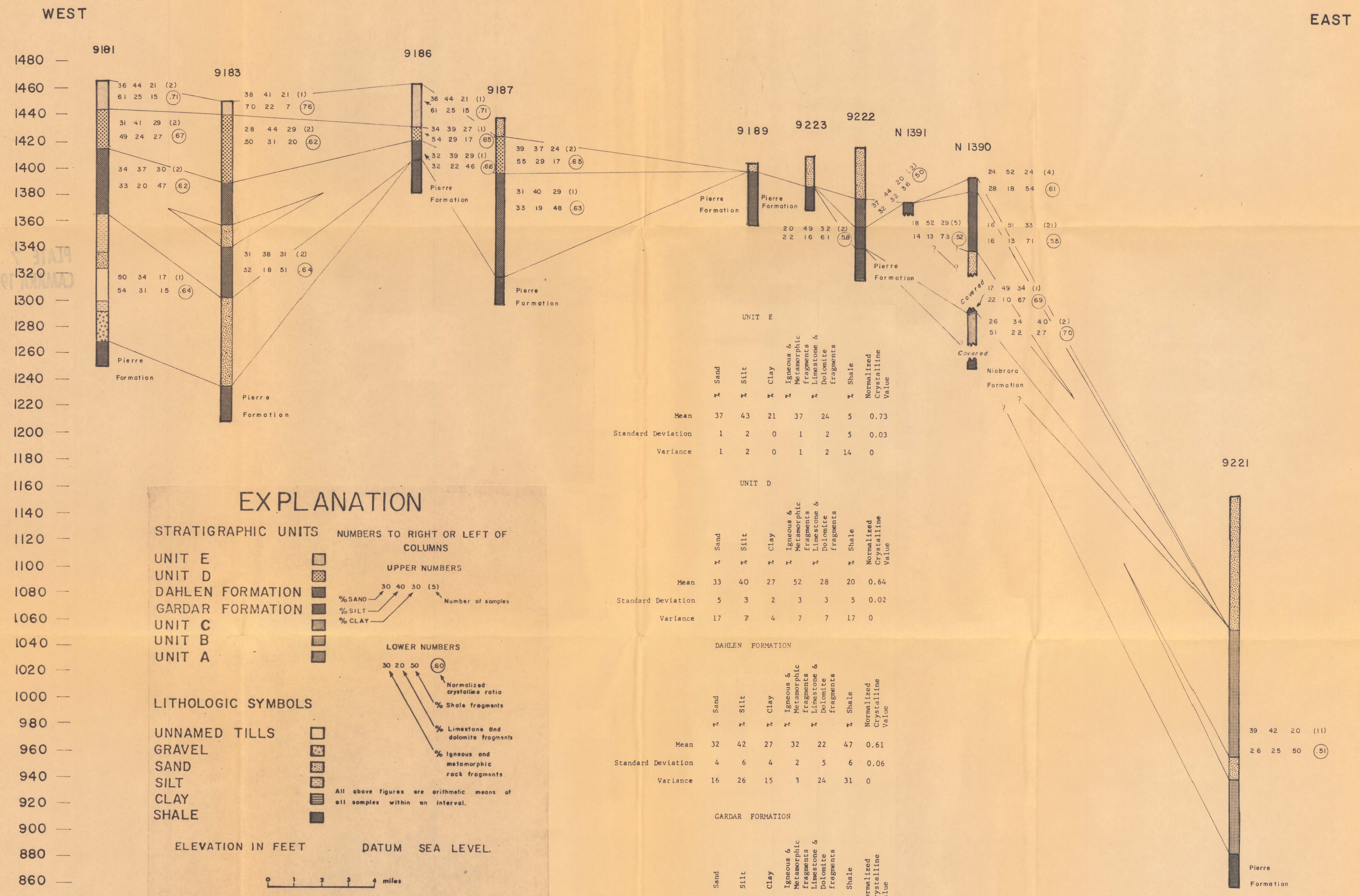
UNIT D

	% Sand	% Silt	% Clay	% Igneous & Metamorphic fragments	% Limestone & Dolomite fragments	% Shale	Normalized Crystalline Value
Mean	30	42	28	51	27	22	0.65
Standard Deviation	3	4	4	6	2	7	0.03
Variance	9	12	14	36	3	42	0

DAHLEN FORMATION

	% Sand	% Silt	% Clay	% Igneous & Metamorphic fragments	% Limestone & Dolomite fragments	% Shale	Normalized Crystalline Value
Mean	32	39	27	28	22	49	0.57
Standard Deviation	6	5	5	4	3	6	0.06
Variance	37	24	19	14	10	37	0

PLATE 7 STRATIGRAPHIC CROSS SECTION FROM ADRIAN TO ENDERLIN



EXPLANATION

STRATIGRAPHIC UNITS

UNIT E
UNIT D
DAHLEN FORMATION
GARDAR FORMATION
UNIT C
UNIT B
UNIT A

LITHOLOGIC SYMBOLS

UNNAMED TILLS
GRAVEL
SAND
SILT
CLAY
SHALE

NUMBERS TO RIGHT OR LEFT OF COLUMNS

UPPER NUMBERS

30 40 30 (5) — % SAND, % SILT, % CLAY, Number of samples

LOWER NUMBERS

30 20 50 (60) — % Igneous and metamorphic rock fragments, % Limestone and dolomite fragments, % Shale fragments, Normalized crystalline ratio

All above figures are arithmetic means of all samples within an interval.

ELEVATION IN FEET DATUM SEA LEVEL.

0 1 2 3 4 miles

0 2 4 kilometers

UNIT E

	% Sand	% Silt	% Clay	% Igneous & Metamorphic fragments	% Limestone & Dolomite fragments	% Shale	Normalized Crystalline Value
Mean	37	43	21	37	24	5	0.73
Standard Deviation	1	2	0	1	2	5	0.03
Variance	1	2	0	1	2	14	0

UNIT D

	% Sand	% Silt	% Clay	% Igneous & Metamorphic fragments	% Limestone & Dolomite fragments	% Shale	Normalized Crystalline Value
Mean	33	40	27	52	28	20	0.64
Standard Deviation	5	3	2	3	3	5	0.02
Variance	17	7	4	7	7	17	0

DAHLEN FORMATION

	% Sand	% Silt	% Clay	% Igneous & Metamorphic fragments	% Limestone & Dolomite fragments	% Shale	Normalized Crystalline Value
Mean	32	42	27	32	22	47	0.61
Standard Deviation	4	6	4	2	5	6	0.06
Variance	16	26	15	3	24	31	0

GARDAR FORMATION

	% Sand	% Silt	% Clay	% Igneous & Metamorphic fragments	% Limestone & Dolomite fragments	% Shale	Normalized Crystalline Value
Mean	18	50	32	19	13	68	0.59
Standard Deviation	2	2	2	4	2	5	0.07
Variance	2	2	4	13	5	21	0

PLATE 6 STRATIGRAPHIC CROSS SECTION ALONG THE SHEYENNE RIVER TRENCH

UNIT D

	% Sand	% Silt	% Clay	% Igneous & Metamorphic fragments	% Limestone & Dolomite fragments	% Shale	Normalized Crystalline Value
Mean	34	37	31	48	30	22	0.62
Standard Deviation	10	9	12	5	2	6	0.02
Variance	73	60	109	19	2	29	0

DAHLEN FORMATION

	% Sand	% Silt	% Clay	% Igneous & Metamorphic fragments	% Limestone & Dolomite fragments	% Shale	Normalized Crystalline Value
Mean	26	45	30	29	22	49	0.57
Standard Deviation	7	6	10	5	5	7	0.07
Variance	43	28	100	21	28	51	0

GARDAR FORMATION

	% Sand	% Silt	% Clay	% Igneous & Metamorphic fragments	% Limestone & Dolomite fragments	% Shale	Normalized Crystalline Value
Mean	21	43	37	18	16	66	0.54
Standard Deviation	6	9	9	6	5	8	0.08
Variance	34	70	81	37	22	57	0.01

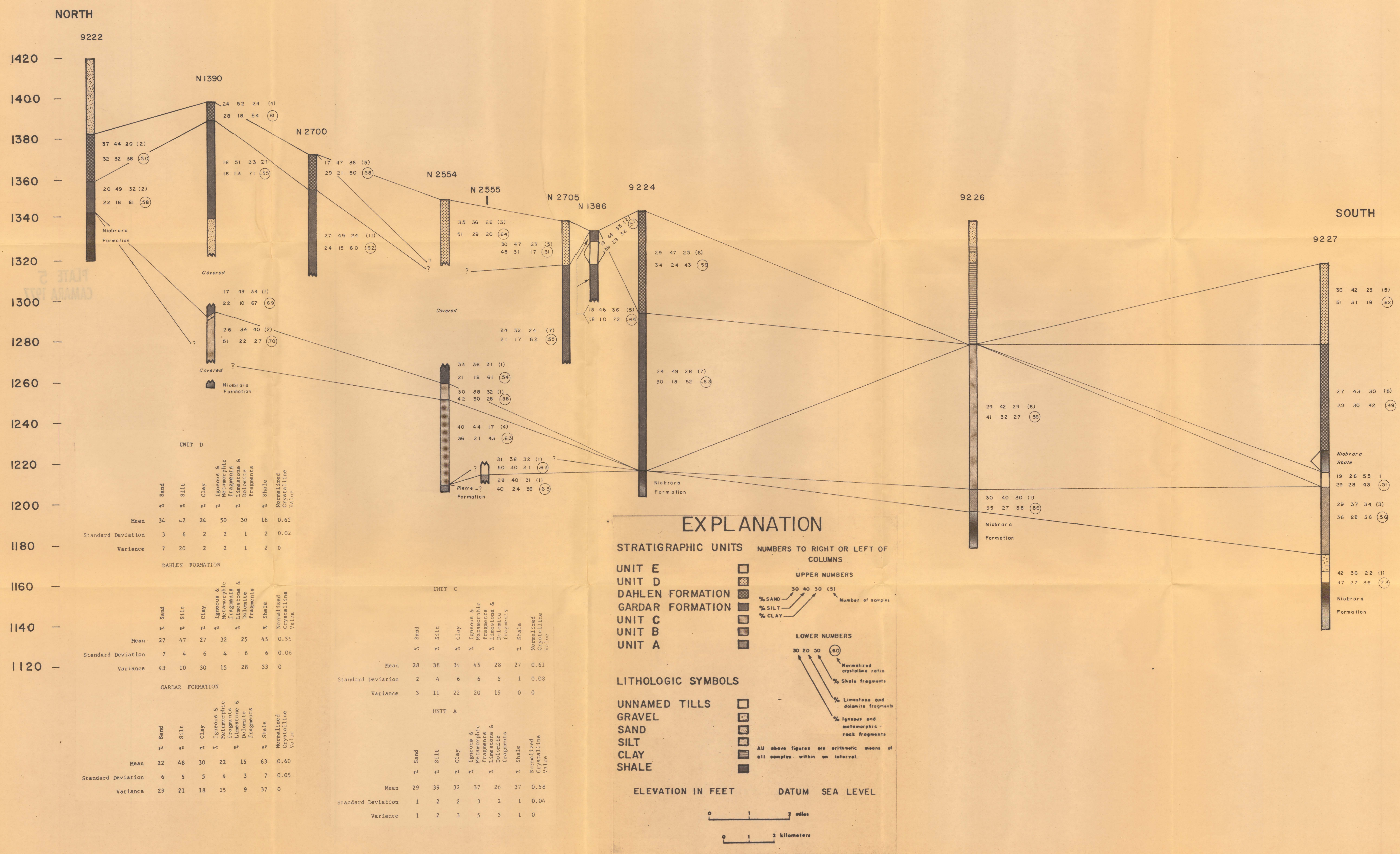
UNIT C

	% Sand	% Silt	% Clay	% Igneous & Metamorphic fragments	% Limestone & Dolomite fragments	% Shale	Normalized Crystalline Value
Mean	38	37	26	36	31	33	0.54
Standard Deviation	9	10	8	6	6	5	0.08
Variance	70	96	58	34	37	26	0.01

UNIT B

	% Sand	% Silt	% Clay	% Igneous & Metamorphic fragments	% Limestone & Dolomite fragments	% Shale	Normalized Crystalline Value
Mean	35	41	24	29	25	47	0.55
Standard Deviation	2	3	5	7	6	4	0.09
Variance	3	4	14	29	20	10	0

PLATE 5 STRATIGRAPHIC CROSS SECTION OF WESTERN RANSOM COUNTY



UNIT D

	% Sand	% Silt	% Clay	% Igneous & Metamorphic fragments	% Limestone & Dolomite fragments	% Shale	Normalized Crystalline Value
Mean	34	42	24	50	30	18	0.62
Standard Deviation	3	6	2	2	1	2	0.02
Variance	7	20	2	2	1	2	0

DAHLEN FORMATION

	% Sand	% Silt	% Clay	% Igneous & Metamorphic fragments	% Limestone & Dolomite fragments	% Shale	Normalized Crystalline Value
Mean	27	47	27	32	25	45	0.55
Standard Deviation	7	4	6	4	6	6	0.06
Variance	43	10	30	15	28	33	0

GARDAR FORMATION

	% Sand	% Silt	% Clay	% Igneous & Metamorphic fragments	% Limestone & Dolomite fragments	% Shale	Normalized Crystalline Value
Mean	22	48	30	22	15	63	0.60
Standard Deviation	6	5	5	4	3	7	0.05
Variance	29	21	18	15	9	37	0

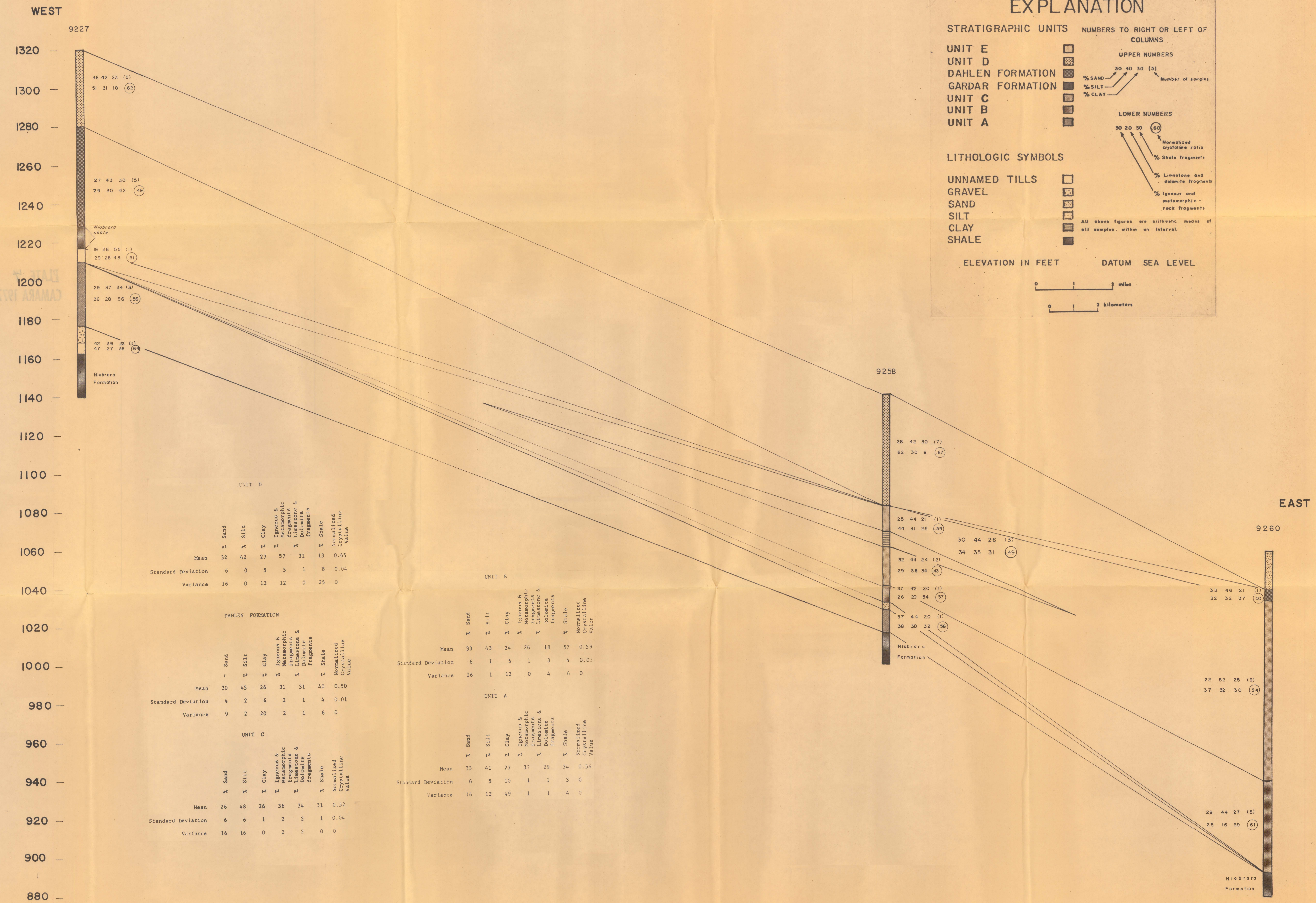
UNIT C

	% Sand	% Silt	% Clay	% Igneous & Metamorphic fragments	% Limestone & Dolomite fragments	% Shale	Normalized Crystalline Value
Mean	28	38	34	45	28	27	0.61
Standard Deviation	2	4	6	6	5	1	0.08
Variance	3	11	22	20	19	0	0

UNIT A

	% Sand	% Silt	% Clay	% Igneous & Metamorphic fragments	% Limestone & Dolomite fragments	% Shale	Normalized Crystalline Value
Mean	29	39	32	37	26	37	0.58
Standard Deviation	1	2	2	3	2	1	0.04
Variance	1	2	3	5	3	1	0

PLATE 4 STRATIGRAPHIC CROSS SECTION OF NORTHERN SARGENT COUNTY



UNIT D

	% Sand	% Silt	% Clay	% Igneous & Metamorphic fragments	% Limestone & Dolomite fragments	% Shale	Normalized Crystalline Value
Mean	32	42	27	57	31	13	0.65
Standard Deviation	6	0	5	5	1	8	0.04
Variance	16	0	12	12	0	25	0

DAHLEN FORMATION

	% Sand	% Silt	% Clay	% Igneous & Metamorphic fragments	% Limestone & Dolomite fragments	% Shale	Normalized Crystalline Value
Mean	30	45	26	31	31	40	0.50
Standard Deviation	4	2	6	2	1	4	0.01
Variance	9	2	20	2	1	6	0

UNIT C

	% Sand	% Silt	% Clay	% Igneous & Metamorphic fragments	% Limestone & Dolomite fragments	% Shale	Normalized Crystalline Value
Mean	26	48	26	36	34	31	0.52
Standard Deviation	6	6	1	2	2	1	0.04
Variance	16	16	0	2	2	0	0

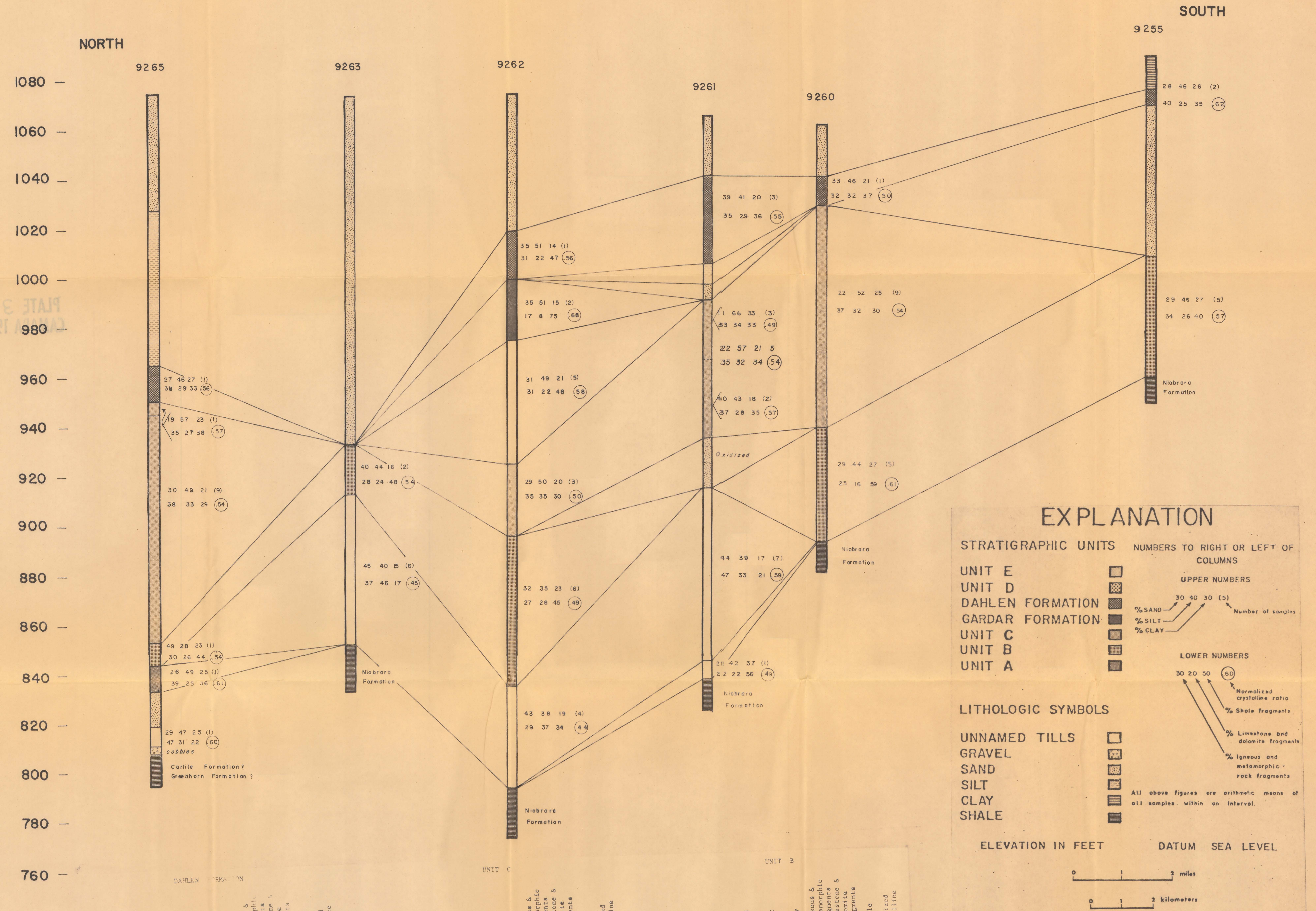
UNIT B

	% Sand	% Silt	% Clay	% Igneous & Metamorphic fragments	% Limestone & Dolomite fragments	% Shale	Normalized Crystalline Value
Mean	33	43	24	26	18	57	0.59
Standard Deviation	6	1	5	1	3	4	0.03
Variance	16	1	12	0	4	6	0

UNIT A

	% Sand	% Silt	% Clay	% Igneous & Metamorphic fragments	% Limestone & Dolomite fragments	% Shale	Normalized Crystalline Value
Mean	33	41	27	37	29	34	0.56
Standard Deviation	6	5	10	1	1	3	0
Variance	16	12	49	1	1	4	0

PLATE 3 STRATIGRAPHIC CROSS SECTION OF EASTERN RANSOM COUNTY



DAHLEN FORMATION

	% Sand	% Silt	% Clay	% Igneous & Metamorphic fragments	% Limestone & Dolomite fragments	% Shale	Normalized Crystalline Value
Mean	32	46	22	35	27	38	0.56
Standard Deviation	5	4	5	4	4	5	0.04
Variance	20	10	22	12	12	24	0

UNIT C

	% Sand	% Silt	% Clay	% Igneous & Metamorphic fragments	% Limestone & Dolomite fragments	% Shale	Normalized Crystalline Value
Mean	26	52	22	36	33	31	0.53
Standard Deviation	4	4	2	2	1	2	0.02
Variance	14	10	4	2	2	4	0

UNIT B

	% Sand	% Silt	% Clay	% Igneous & Metamorphic fragments	% Limestone & Dolomite fragments	% Shale	Normalized Crystalline Value
Mean	36	39	23	29	24	47	0.55
Standard Deviation	9	8	4	3	5	7	0.04
Variance	60	47	16	9	17	41	0

PLATE 2 CROSS SECTION LOCATION MAP

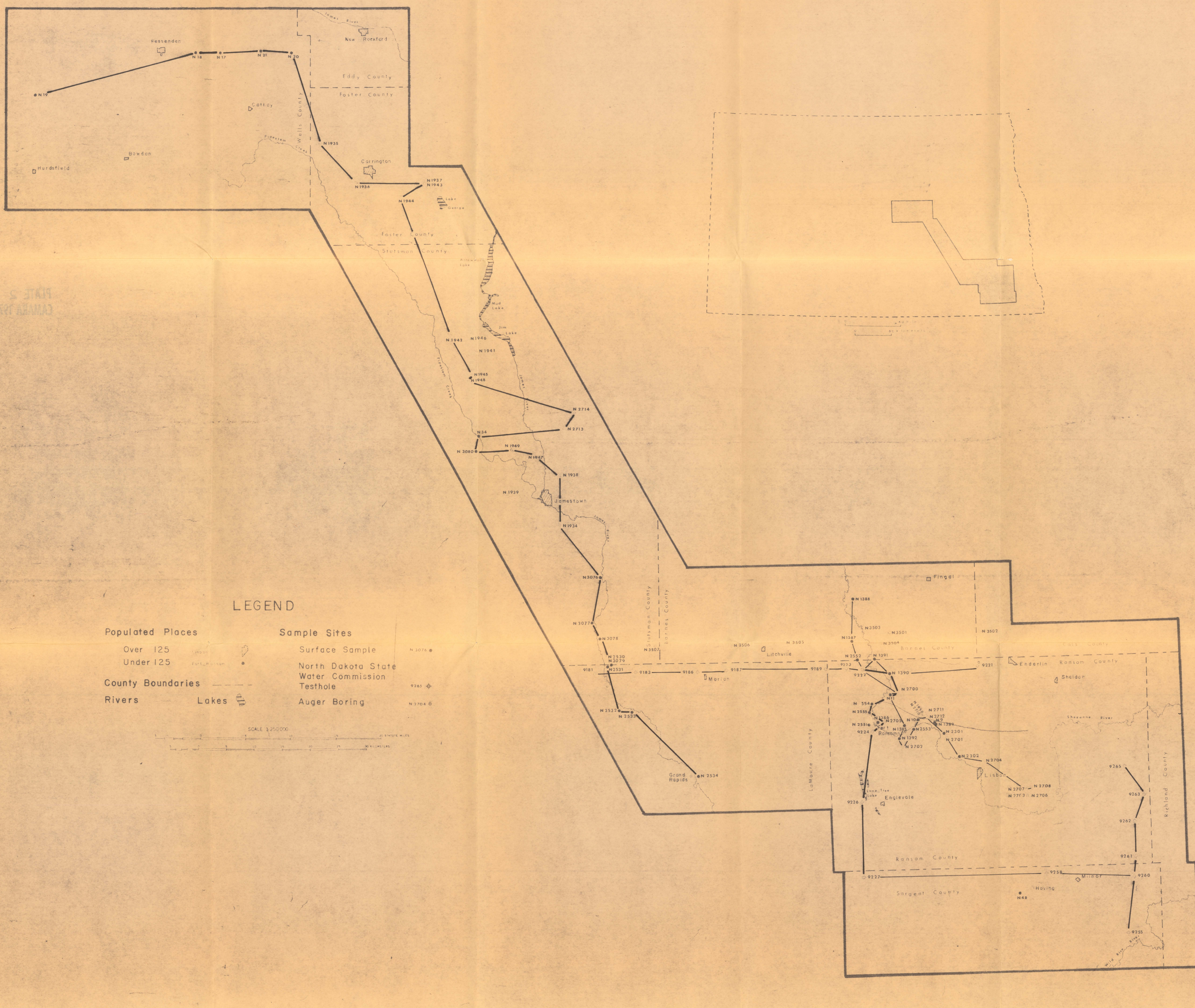


PLATE I SAMPLE LOCATION MAP